

Application of Hybrid RANS-LES to Unsteady Shock-Wave Boundary Layer Interactions in the Presence of a Surface Mounted Protuberance

Kader Frendi and Phil Ligrani



*9th Annual Shock Wave/Boundary Layer Interaction (SWBLI)
Technical Interchange Meeting, May 24-25, Cleveland Ohio*

Outline

- Motivation
- Mathematical Model and Method of Solution
- Problem Setup
- Results
 - Comparison with experimental data
- Wall Pressure Fluctuations
 - The Effect of Protuberance Height
 - The Effect of Surface Curvature
- Conclusions

Motivation

Protuberances are present on most aircraft skins.

Most protuberances exist to accomplish a given task.

The challenge is to understand their effect on the local flow field.

It is also important to understand their effect on the surface pressure distribution in order to avoid potential structural failure.

Experimental data on protuberances is very hard to come by because of its sensitivity.



Mathematical Model

- The RANS model used is the BSL model, which uses (k, ω) near the wall and (k, ε) and away from the wall (Menter).
- A blending function, F_{bsl} , is used to transition between the two models.

$$\nu_t = \frac{k}{\omega}$$

$$\tau'_{ij} = \mu_t \left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) - \frac{2}{3} (\mu_t \nabla \cdot \tilde{\mathbf{u}} + \rho k) \delta_{ij}$$

$$\frac{D\rho k}{Dt} = \tau'_{ij} \frac{\partial u_i}{\partial x_j} - \beta^* \rho \omega k + \frac{\partial}{\partial x_j} \left[(\mu + \mu_t \sigma_k) \frac{\partial k}{\partial x_j} \right]$$

Mathematical Model

$$\frac{D\rho\omega}{Dt} = \frac{\gamma}{v_t} \tau'_{ij} \frac{\partial u_i}{\partial x_j} - \beta \rho \omega^2 + \frac{\partial}{\partial x_j} \left[(\mu + \mu_t \sigma_k) \frac{\partial \omega}{\partial x_j} \right] + 2(1 - F_{bsl}) \rho \sigma_{\omega 2} \frac{1}{\omega} \frac{\partial k}{\partial x_j} \frac{\partial \omega}{\partial x_j}$$

$$F_{bsl} = \tanh(\arg_{bsl}^4)$$

$$\arg_{bsl} = \min \left[\max \left(\frac{\sqrt{k}}{0.09 \omega y}, \frac{500 \nu}{y^2 \omega} \right), \frac{4 \rho \sigma_{\omega 2} k}{CD_{k\omega} y^2} \right]$$

$$\phi = F_{bsl} \phi_1 + (1 - F_{bsl}) \phi_2$$

$$CD_{k\omega} = \max \left(2 \rho \sigma_{\omega 2} \frac{1}{\omega} \frac{\partial k}{\partial x_j} \frac{\partial \omega}{\partial x_j}, 10^{-20} \right)$$

$$\sigma_{k1} = 0.5, \sigma_{\omega 1} = 0.5, \beta_1 = 0.075, \beta^* = 0.09, \kappa = 0.41, \gamma_1 = \frac{\beta_1}{\beta^*} - \frac{\sigma_{\omega 1} \kappa^2}{\sqrt{\beta^*}}$$

$$\sigma_{k2} = 1.0, \sigma_{\omega 2} = 0.856, \beta_2 = 0.0828, \beta^* = 0.09, \kappa = 0.41$$

$$\gamma_2 = \frac{\beta_2}{\beta^*} - \frac{\sigma_{\omega 2} \kappa^2}{\sqrt{\beta^*}}$$

Mathematical Model

We used Nichols and Nelson (2003) Hybrid RANS-LES model

$$L_T = \max \left(6.0 \sqrt{\frac{v_{tRANS}}{\Omega}}, l_T \right) \quad l_T = \frac{\sqrt{k}}{\omega} \quad k_{LES} = k_{RANS} f_d$$

$$f_d = \frac{1}{2} \{1 + \tanh[2\pi(\Lambda - 0.5)]\} \quad \Lambda = \frac{1}{1 + \left(\frac{L_T}{2L_G}\right)^{4/3}} \quad L_G = \max(\Delta x, \Delta y, \Delta z)$$

$$v_T = v_{T RANS} f_d + (1 - f_d) v_{T LES}$$

$$v_{T LES} = \min \left(0.0854 L_G \sqrt{k_{LES}}, v_{T RANS} \right)$$

Method of Solution

Used the Loci-Chem code.

The code is 2nd order accurate in space and time.

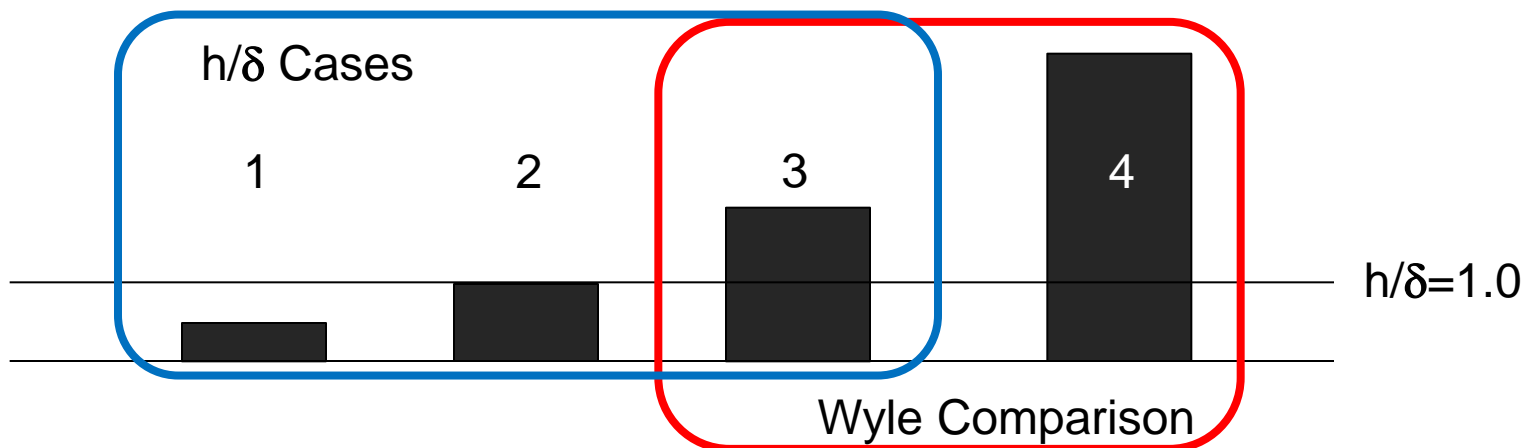
The code accommodates hybrid unstructured grids.

Problem Setup

Test Condition	Value	Uncertainty	Units
M	1.60	± 0.010	-
Re/ft	1.5×10^6	-	-
V_∞	1520	± 0.010	[ft/s]
q_∞	662	± 5 psf	[lb/ft ²]
T	300	$\pm 5^\circ\text{F}$	[$^\circ\text{F}$]
h/D	1.0, 2.0	-	-

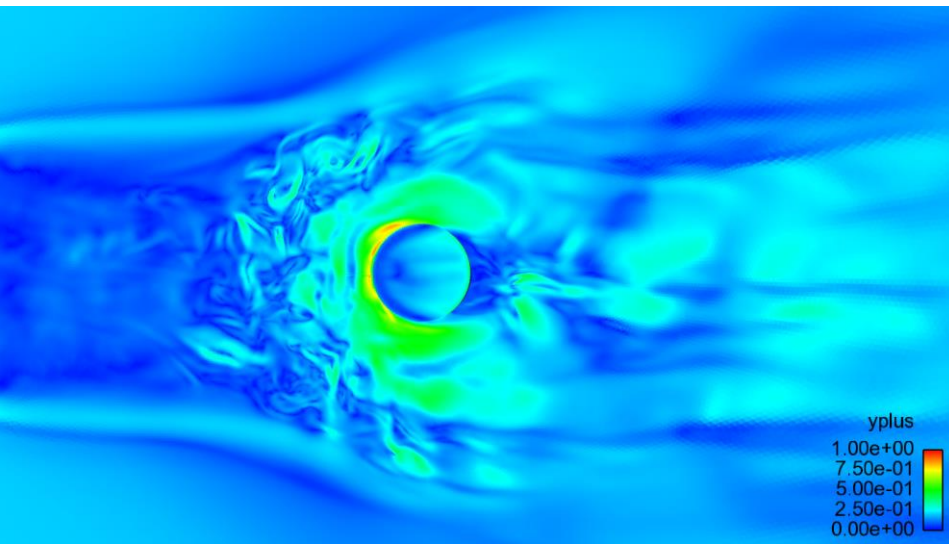
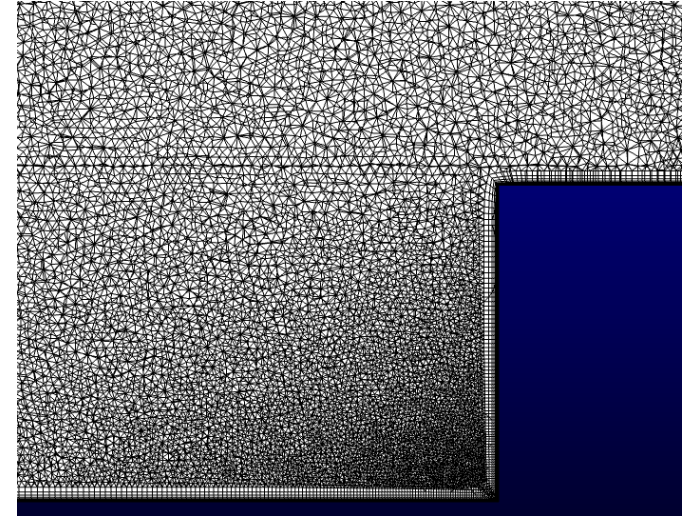
Problem Setup

Case	h/δ	Curvature	Description	Comparison
0	0.00	Flat	Flat Plate	n/a
0-1	0.00	24.375	Curved Plate	n/a
0-2	0.00	12.1875	Curved Plate	n/a
1	0.50	Flat	3D Protuberance	New
2	1.00	Flat	3D Protuberance	New
2-1	1.00	Flat	Grid Resolution Study	n/a
3	2.00	Flat	3D Protuberance	New
3-1	2.00	24.375	3D Protuberance, Curved	Wyle $h/d=1.0$
3-2	2.00	12.1875	3D Protuberance, Curved	New
4	4.00	Flat	3D Protuberance	New
4-1	4.00	24.375	3D Protuberance, Curved	Wyle $h/d=2.0$



Problem Setup

- Wall $y^+ < 1$
- Elements: 55-75 million depending on the protuberance
- Domain Volume: $0.0266 \text{ [m}^3\text{]} \text{ } 0.94 \text{ [ft}^3\text{]}$
- Approximately 150 processors

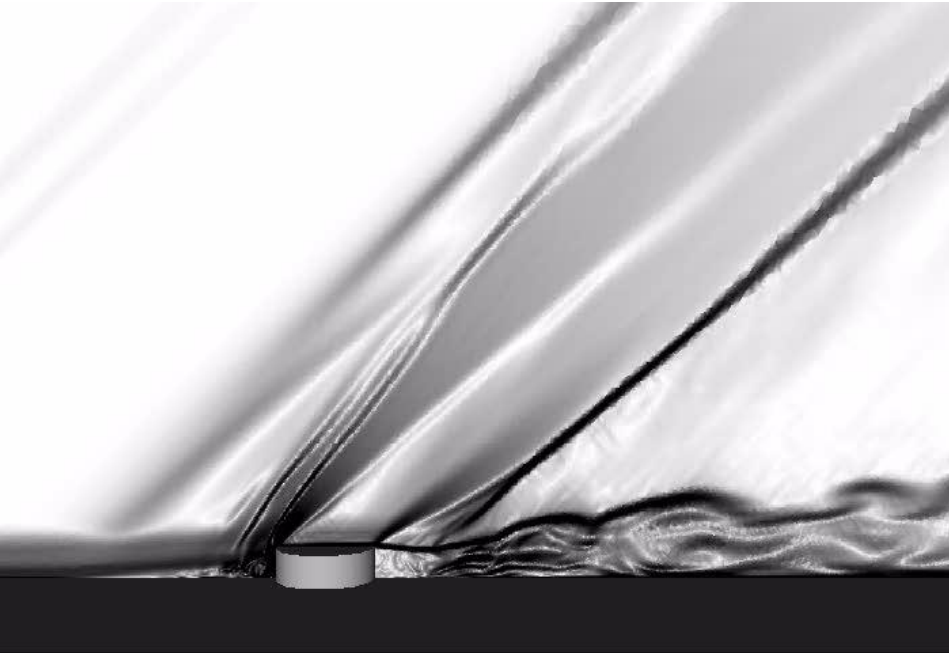


Points Per Inch		
inflow	40	$[\text{in}^{-1}]$
protuberance	200	$[\text{in}^{-1}]$

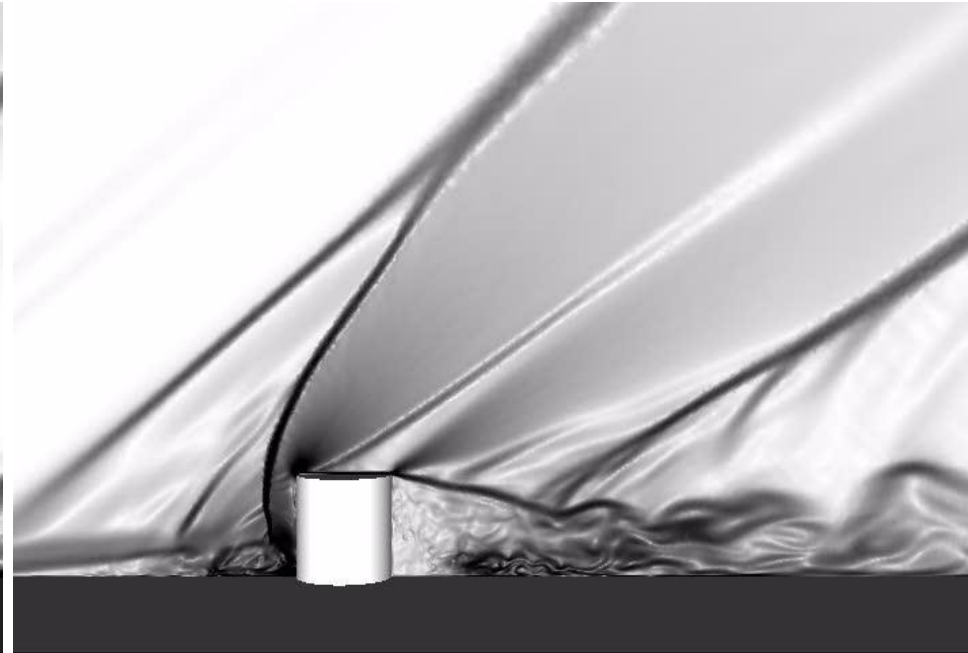
f	λ	λ	$p_{\text{inflow}}/\lambda$	$p_{\text{protuberance}}/\lambda$
[Hz]	[m]	[in]	[]	[]
100	2.8700	112.992	4519.7	22598.4
1,000	0.2870	11.299	452.0	2259.8
10,000	0.0287	1.130	45.2	226.0
25,000	0.0115	0.452	18.1	90.4
50,000	0.0057	0.226	9.0	45.2

Flow Animations

11



$$\frac{h}{\delta} = 0.5$$

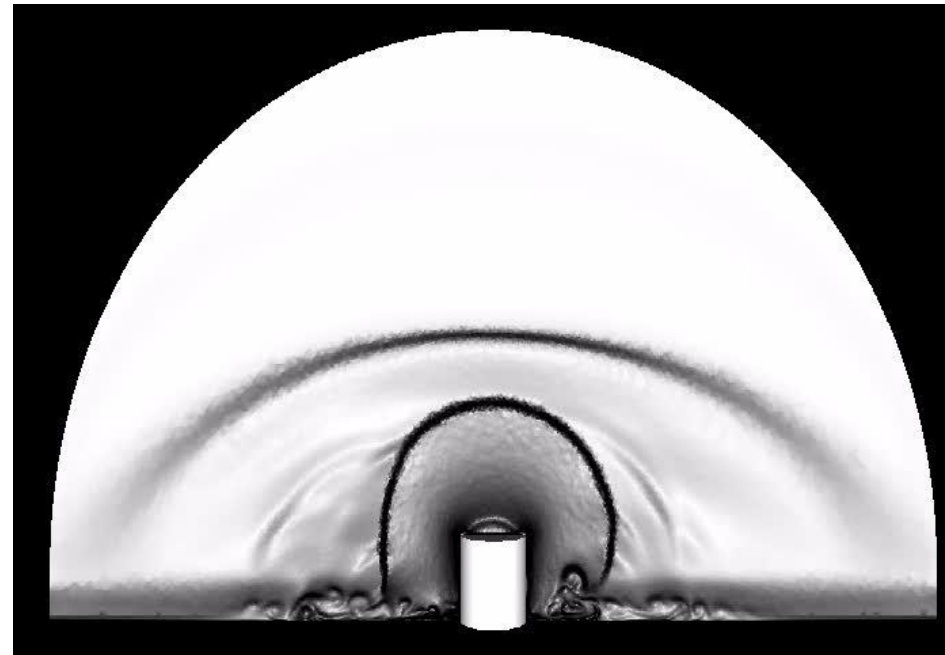


$$\frac{h}{\delta} = 2.0$$

Flow Animations

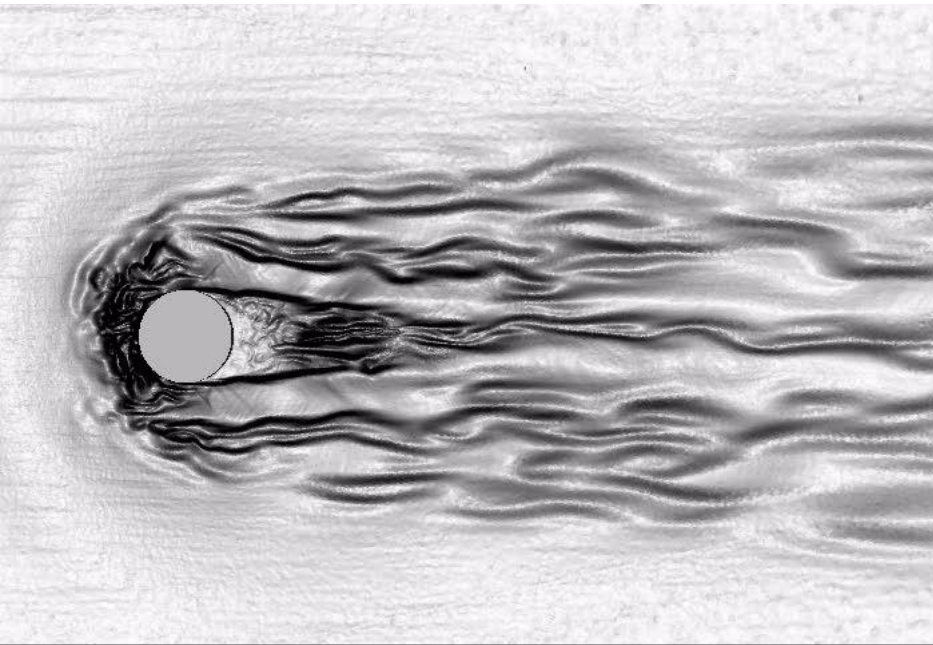


$$\frac{h}{\delta} = 0.5$$

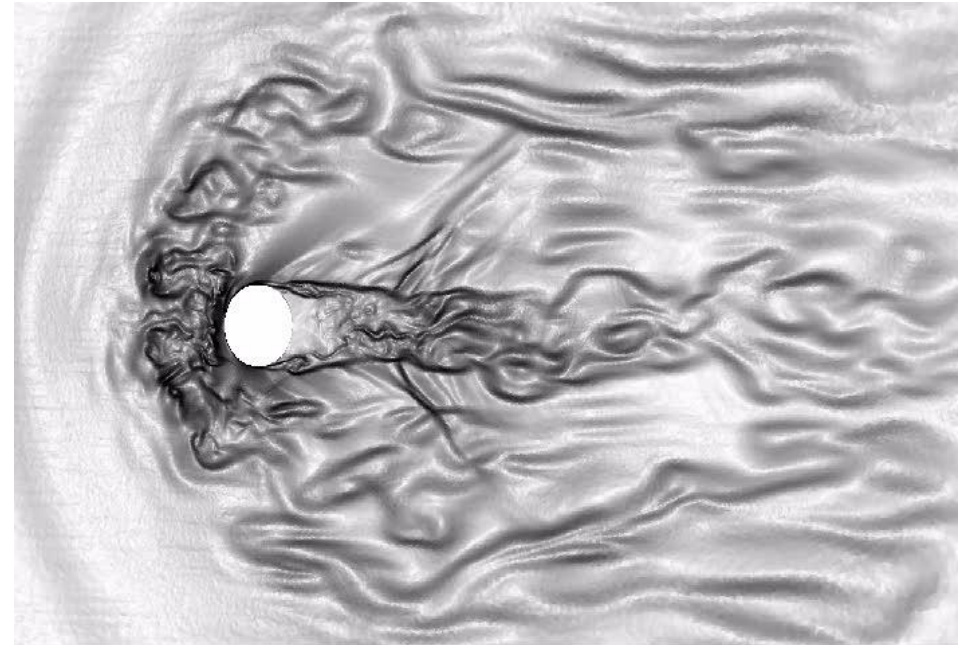


$$\frac{h}{\delta} = 2.0$$

Flow Animations

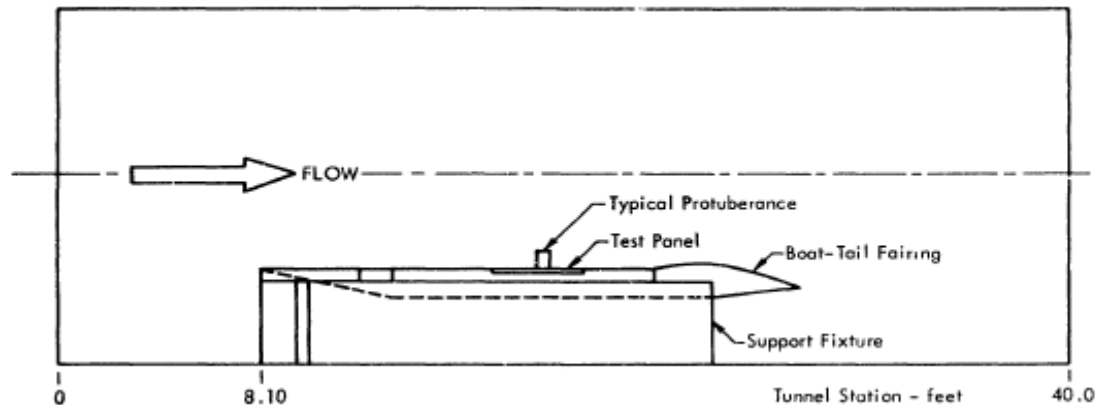
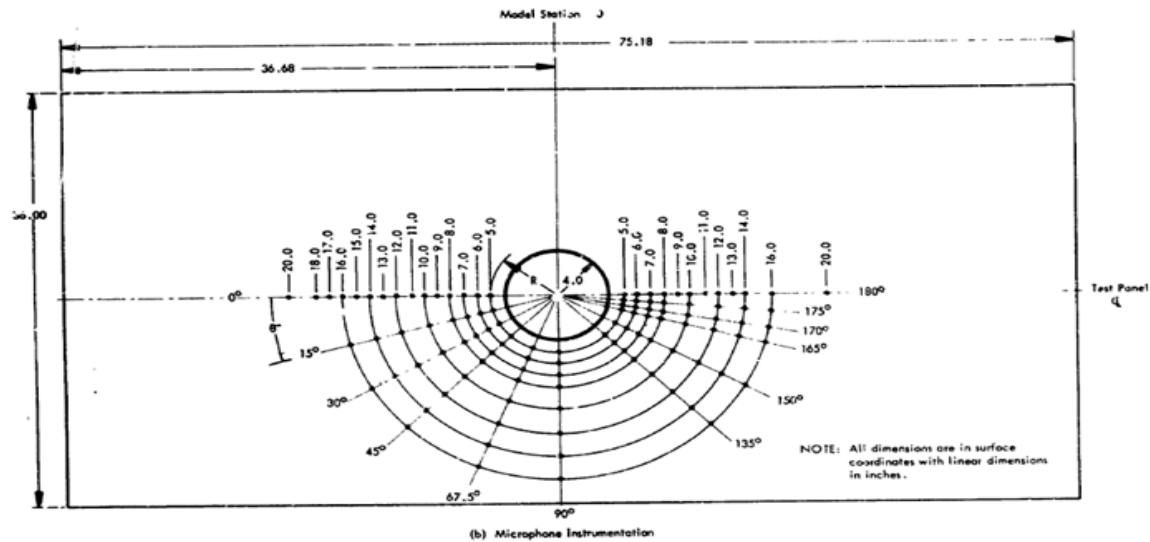


$$\frac{h}{\delta} = 0.5$$

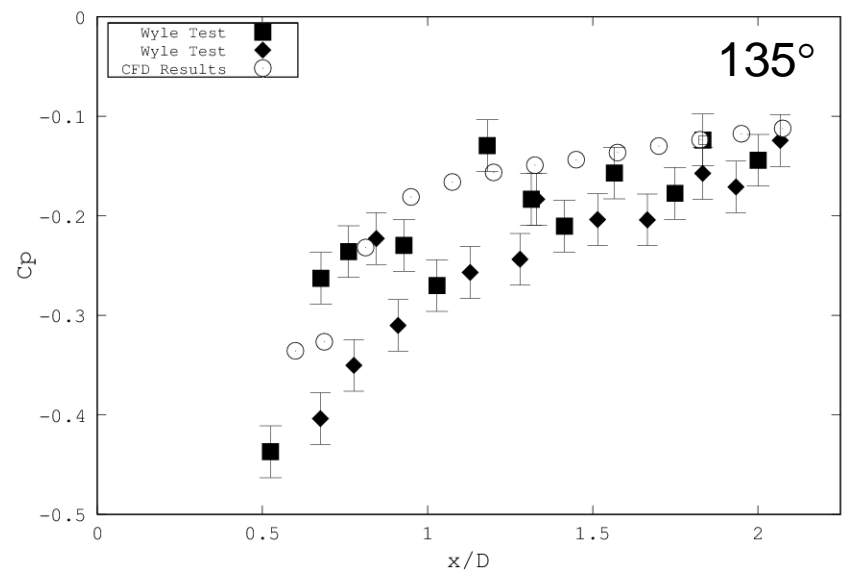
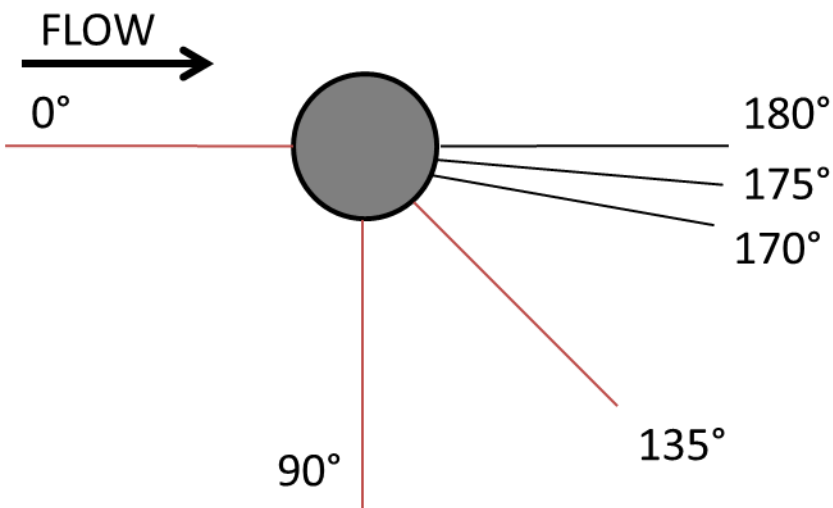
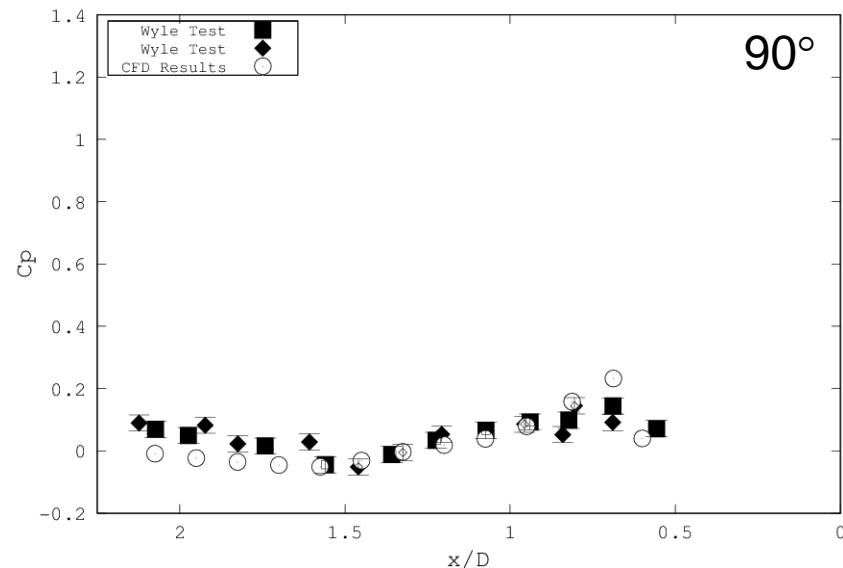
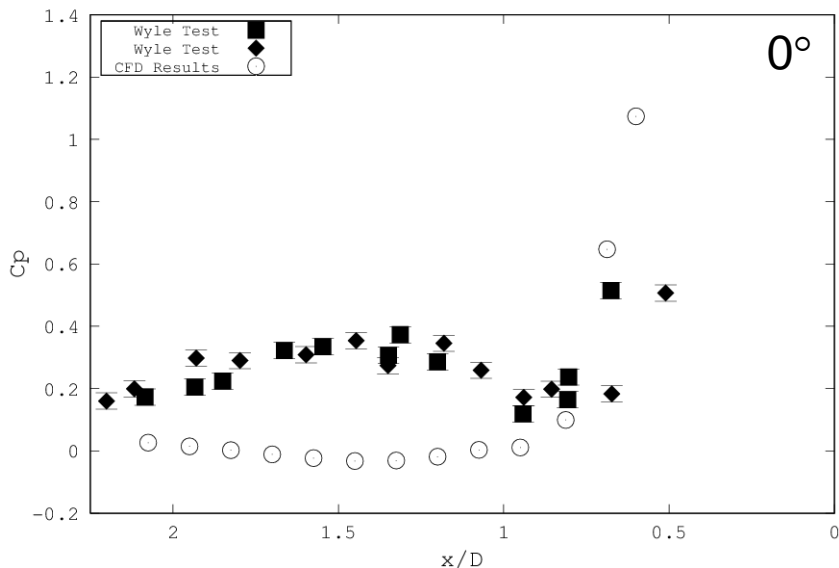


$$\frac{h}{\delta} = 2.0$$

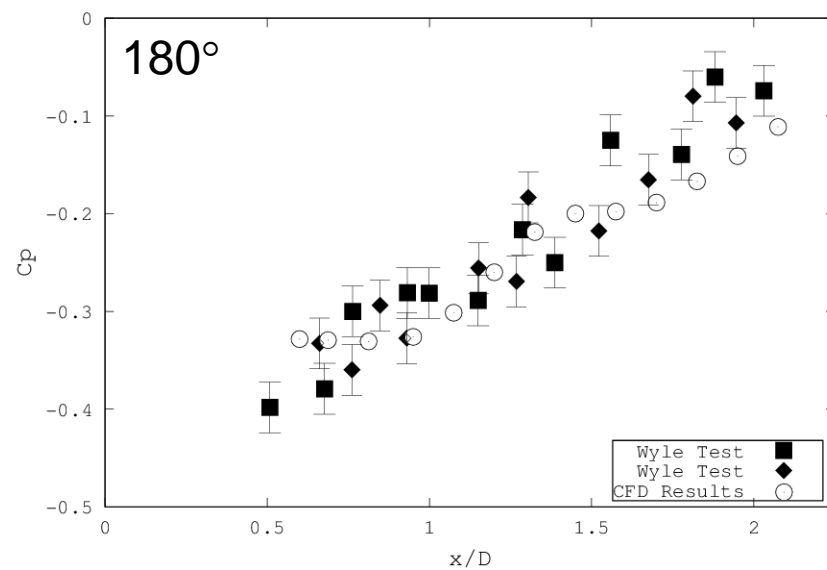
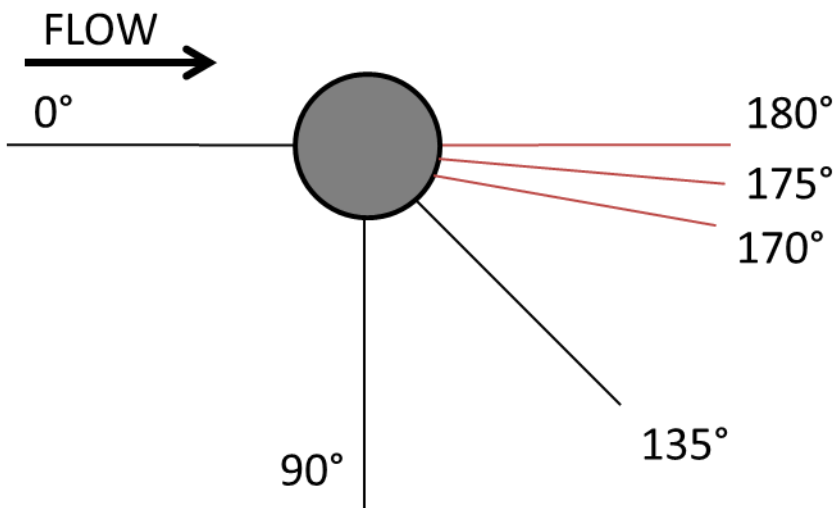
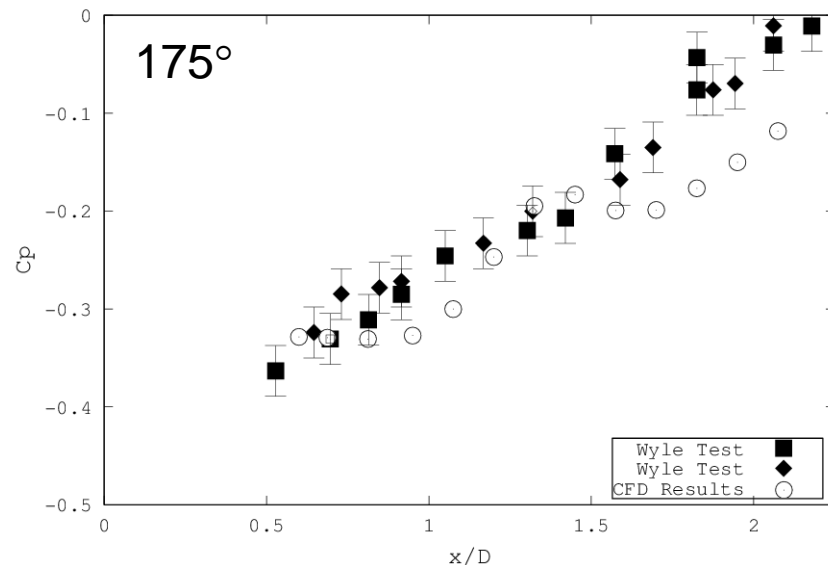
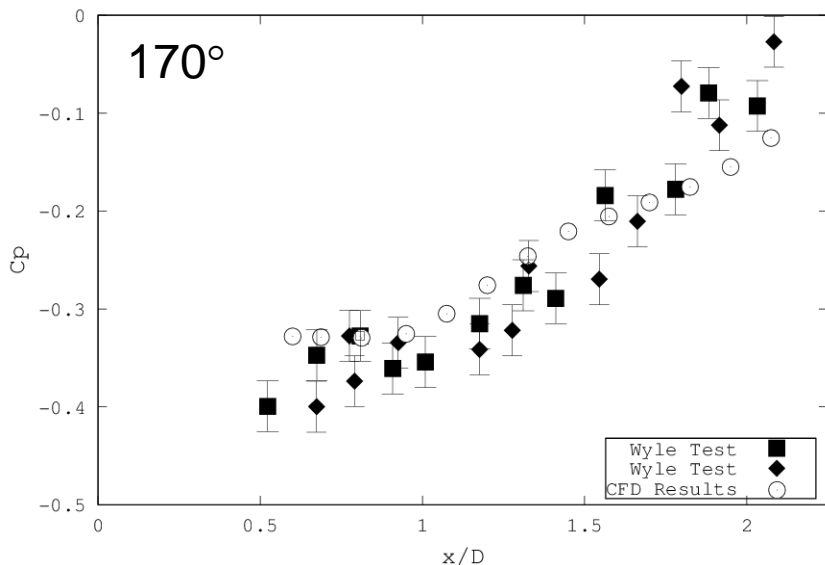
Test Setup



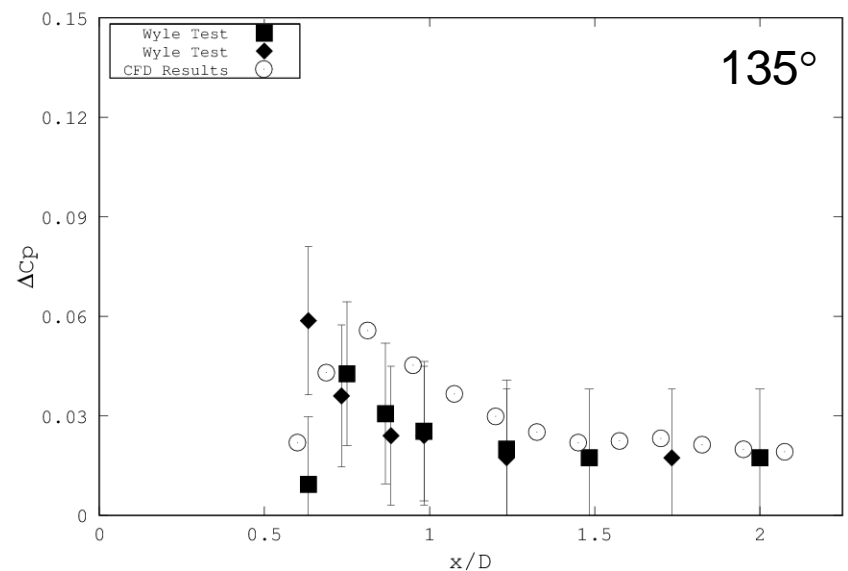
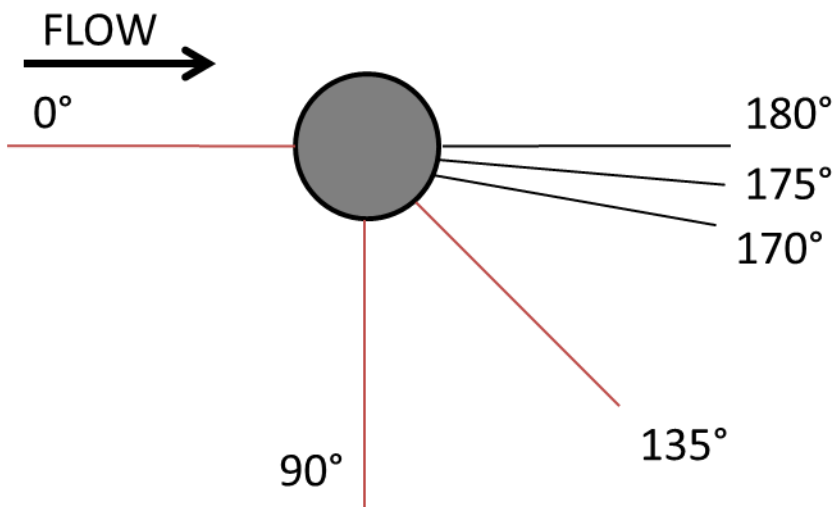
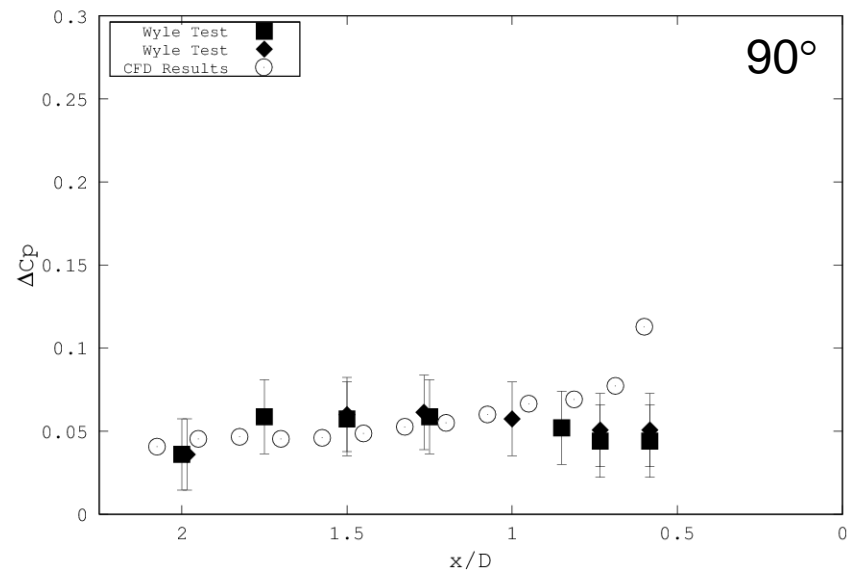
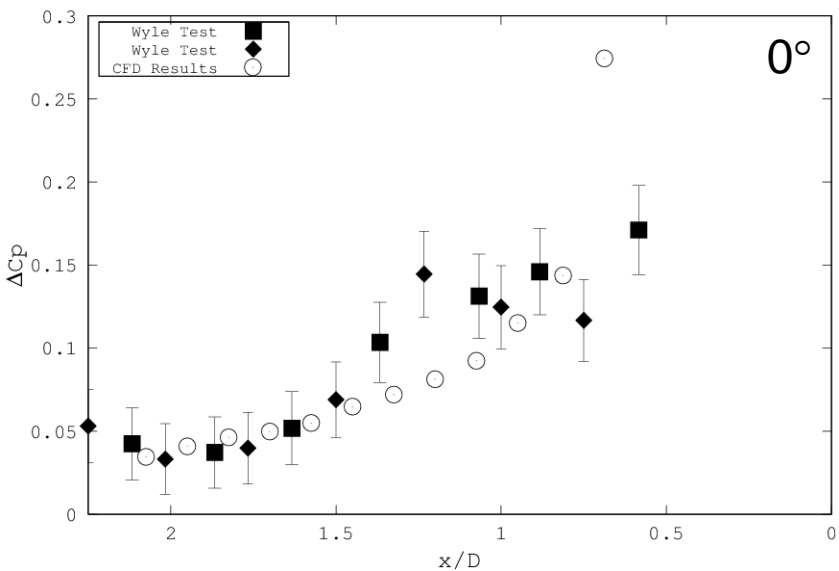
Comparisons with Experiments: C_p for $h/D = 1.0$



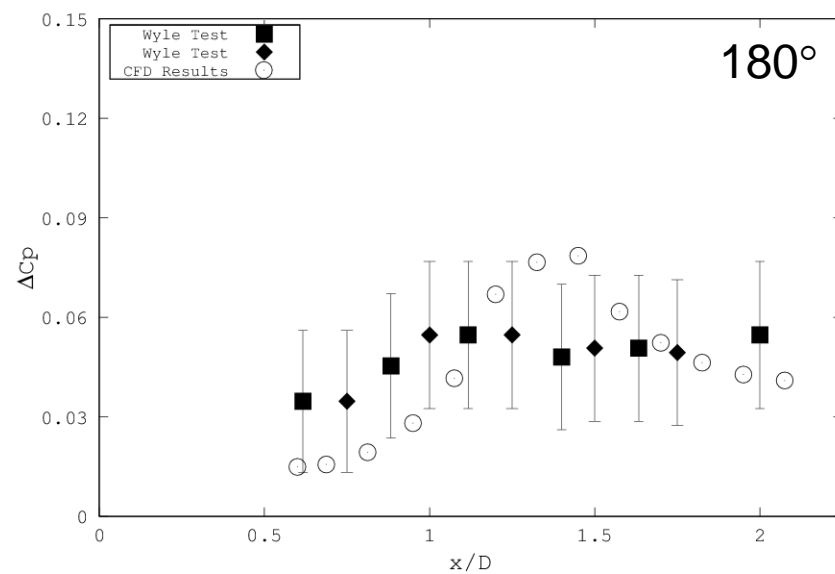
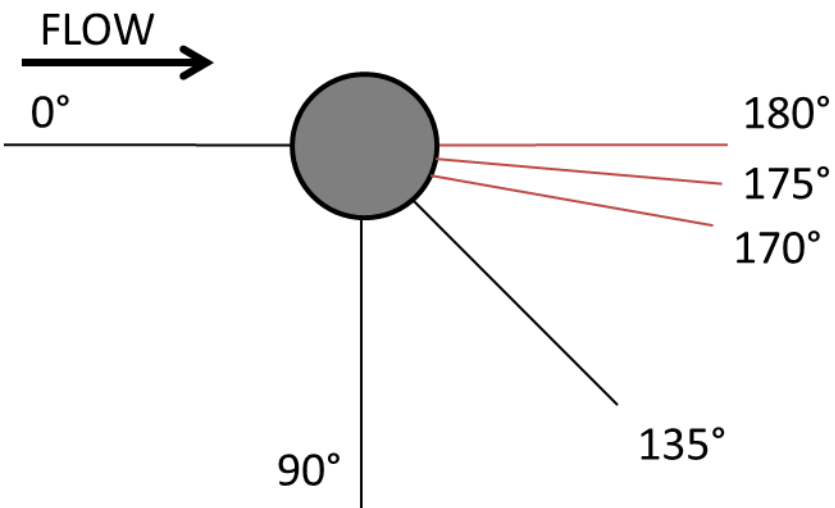
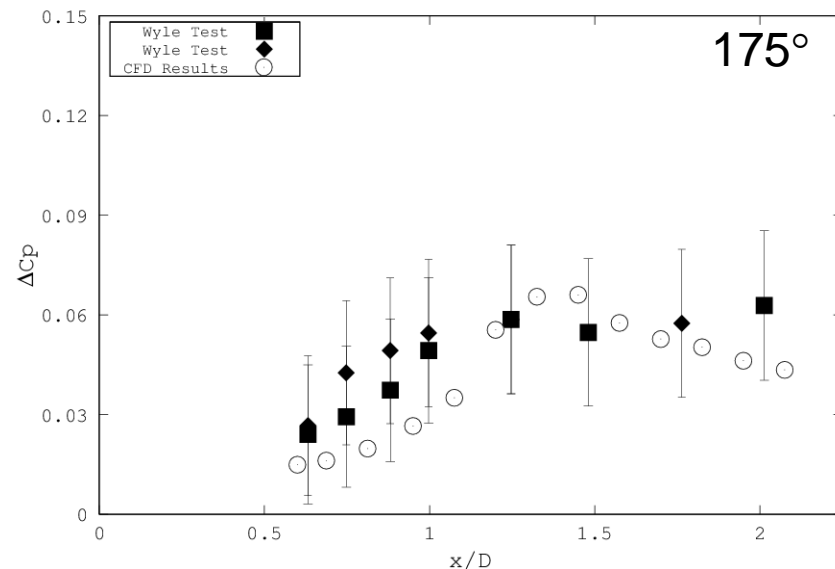
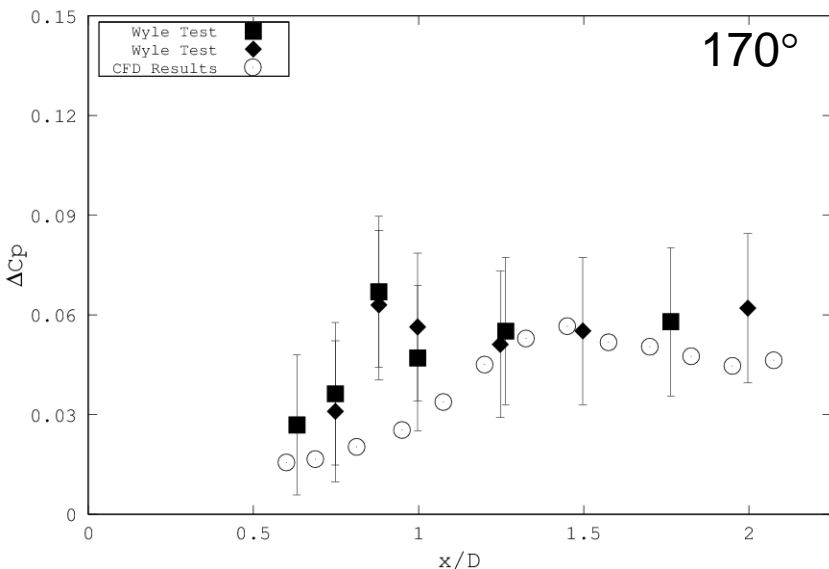
Comparisons with Experiments: C_p for $h/D = 1.0$



Comparisons with experiments: ΔC_p for $h/D = 1.0$

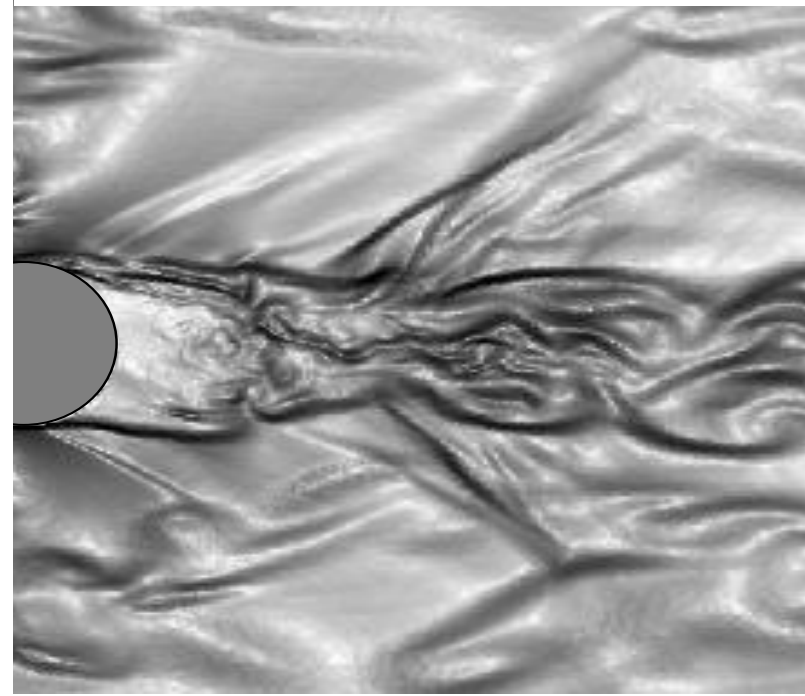
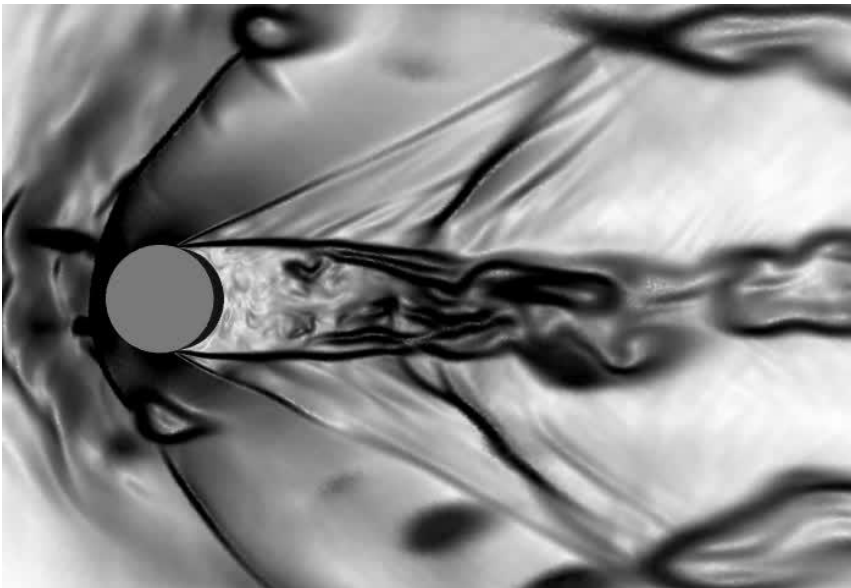
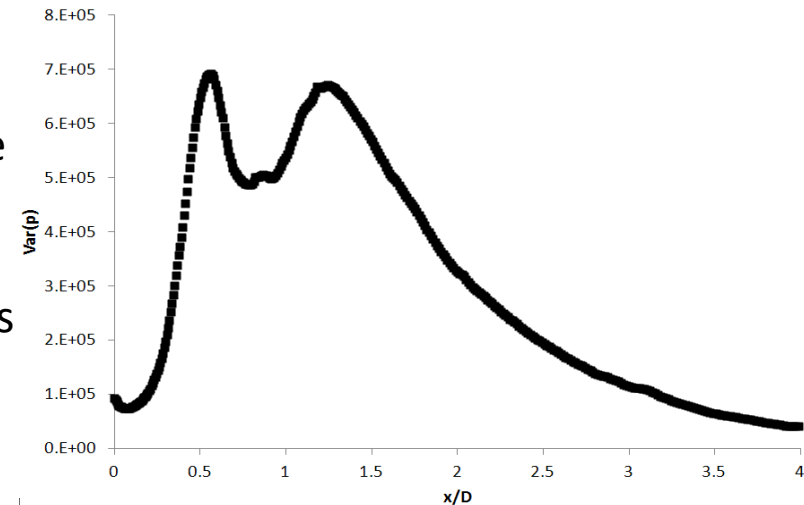


Comparisons with experiments: ΔC_p for $h/D = 1.0$

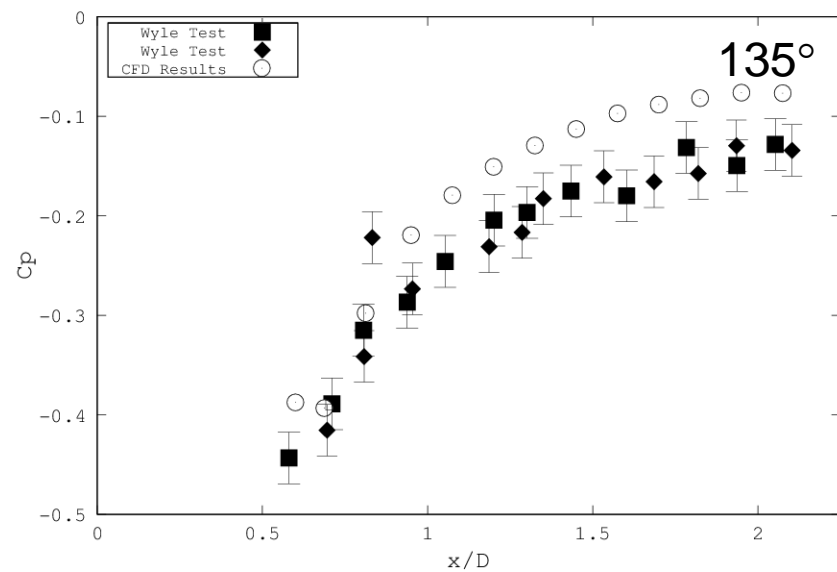
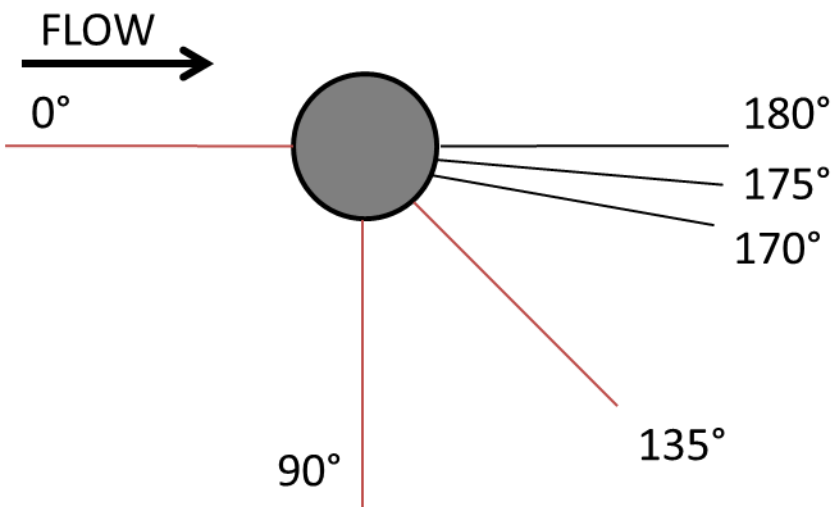
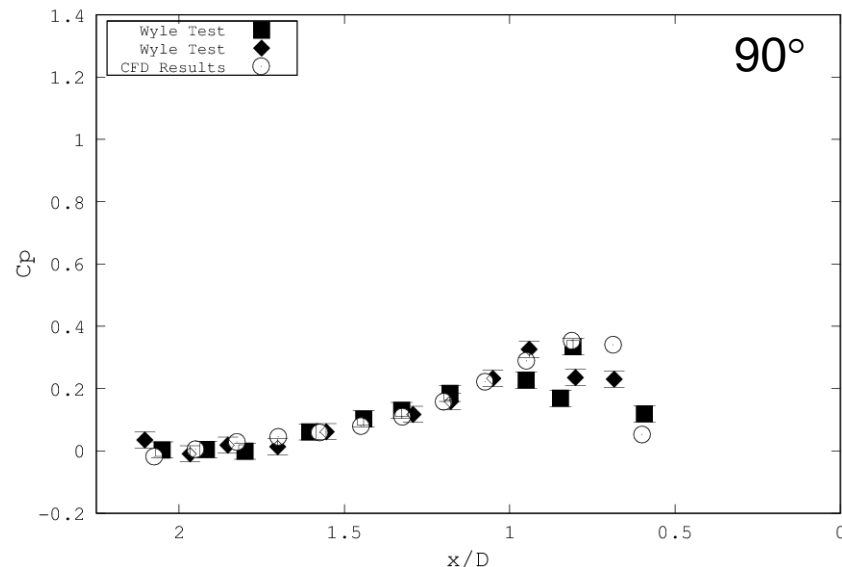
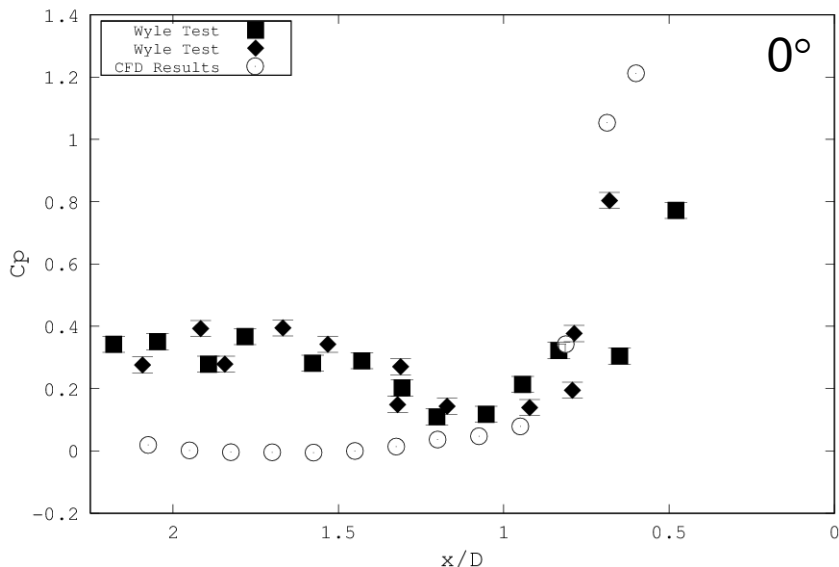


Termination Shock

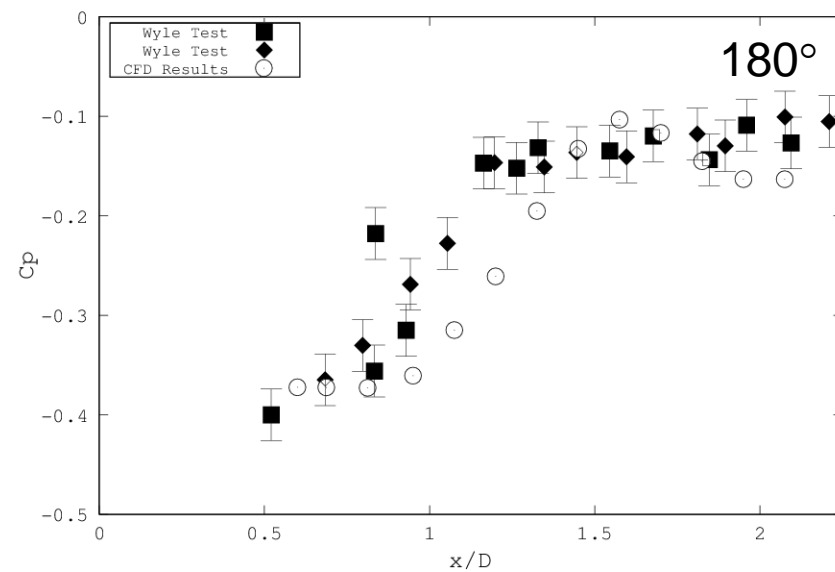
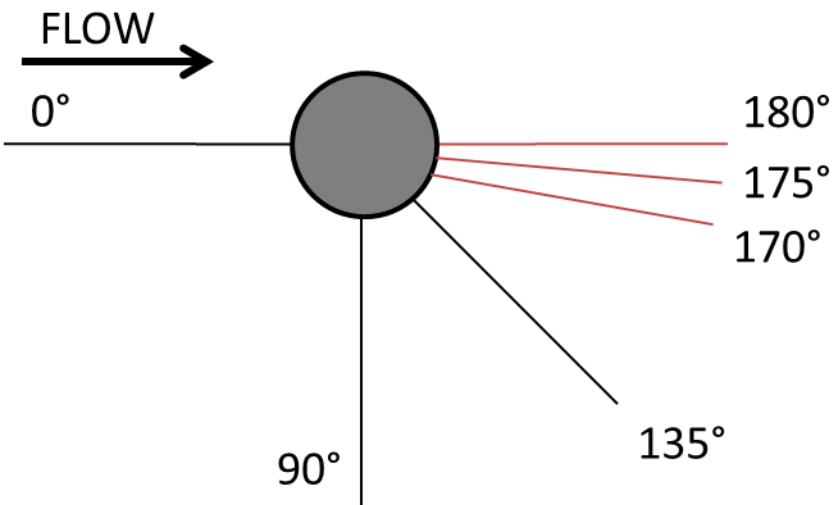
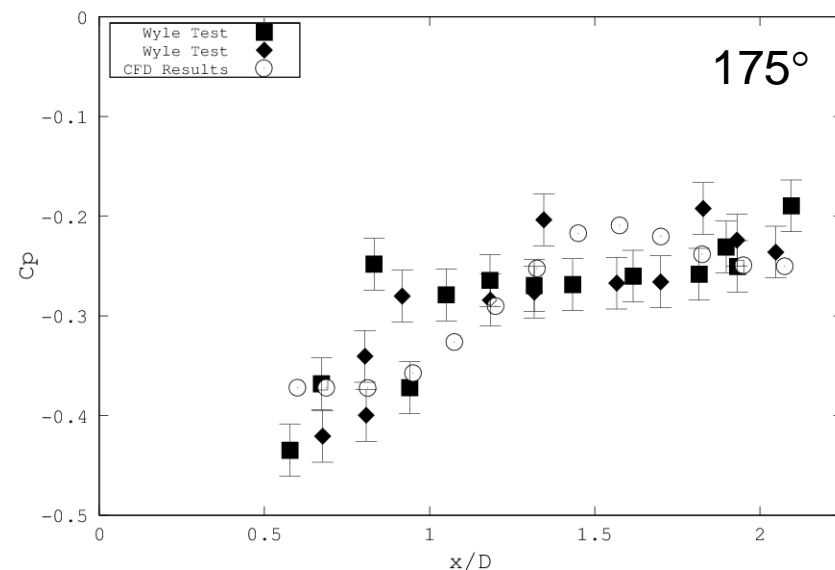
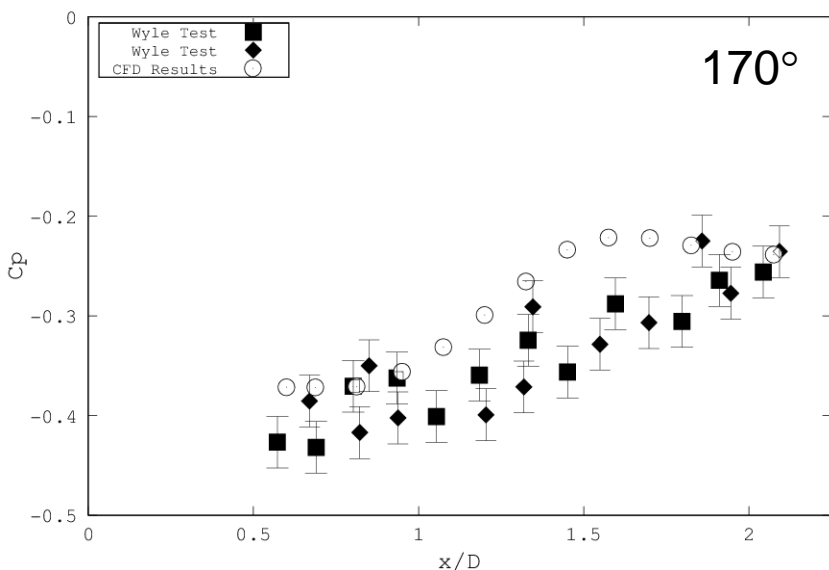
- Termination shock trails the protuberance at approximately $x/D=1.5$ downstream of protuberance
- Termination shock turns the flow parallel to inflow.
- Unsteady shock sweeps fore and aft, changes geometry and strength with collisions of Mach waves and upstream vortex structures.



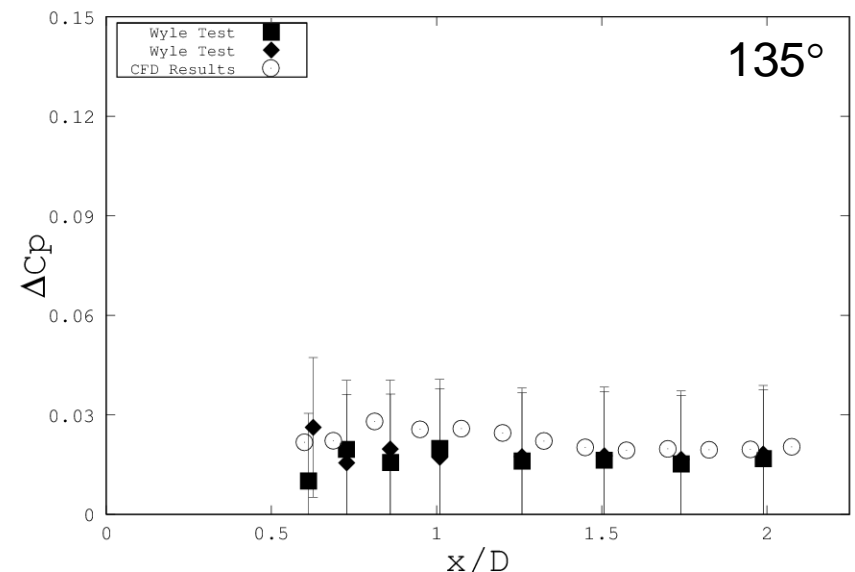
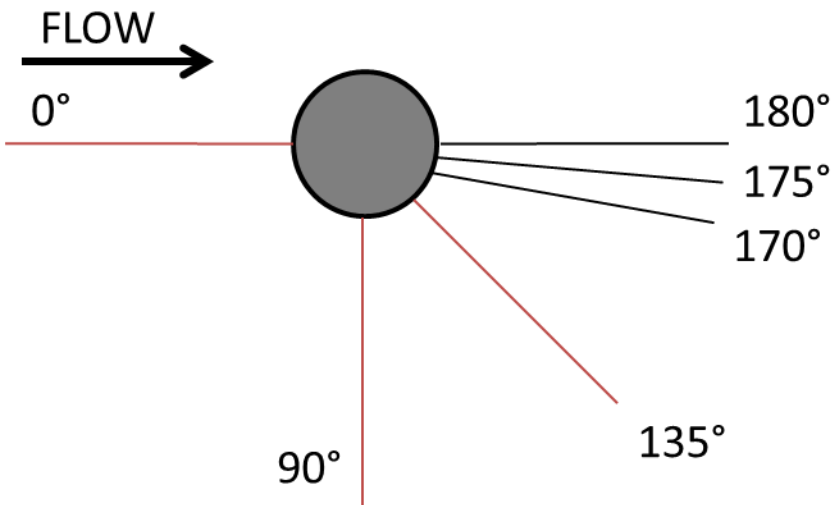
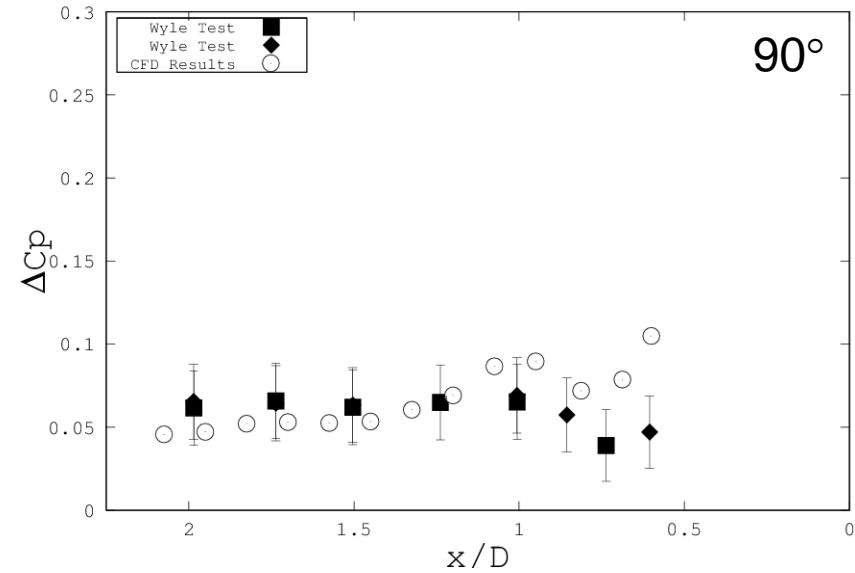
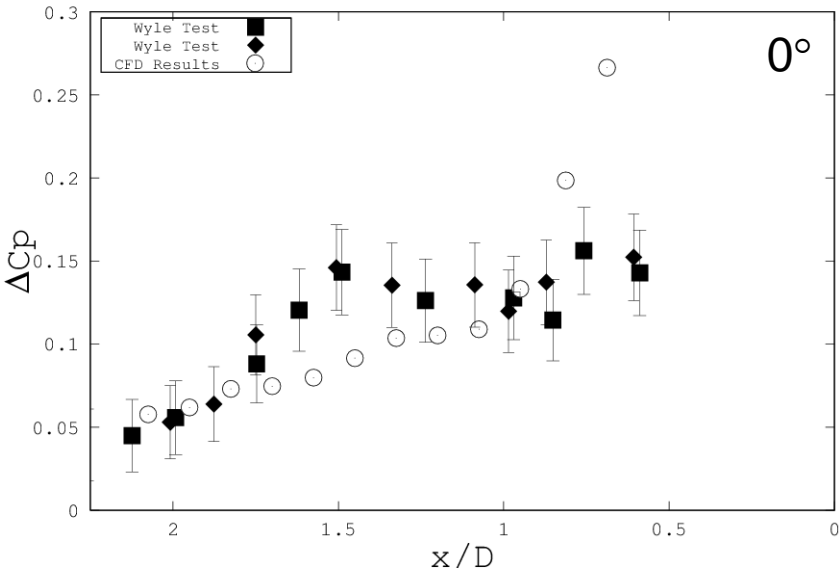
Comparisons with Experiments: C_p for $h/D = 2.0$



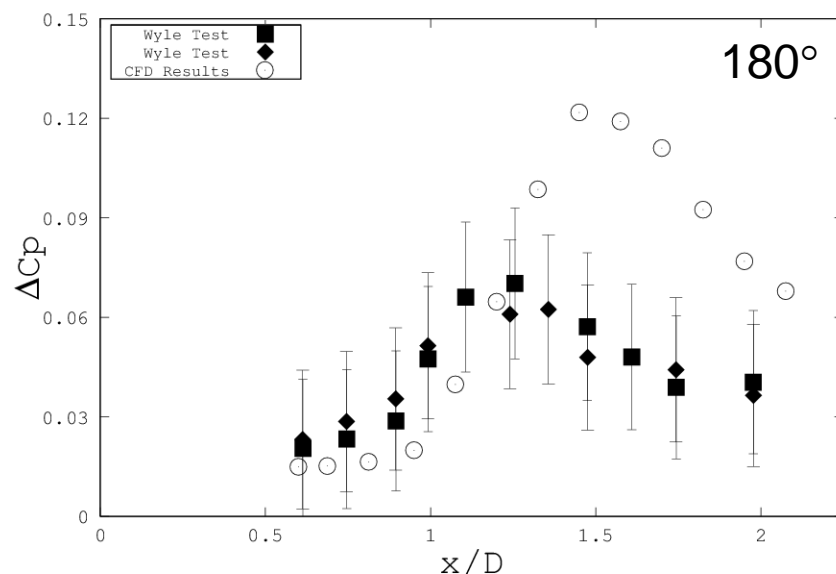
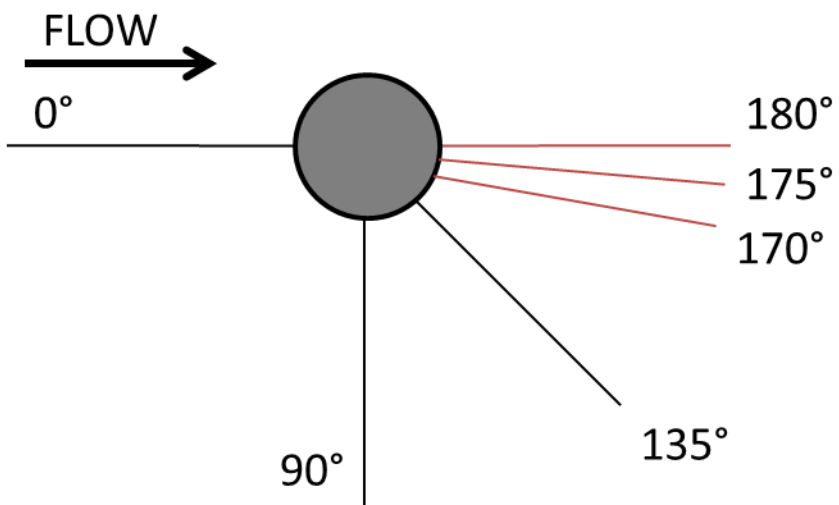
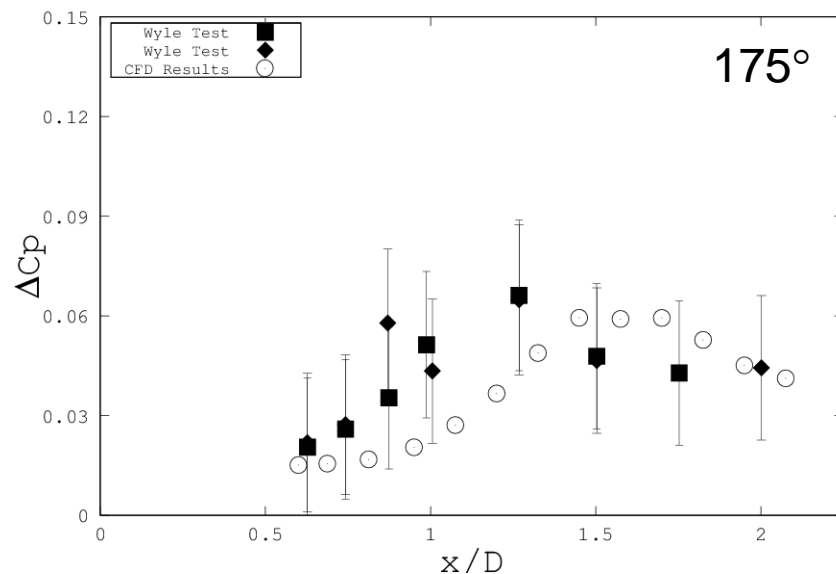
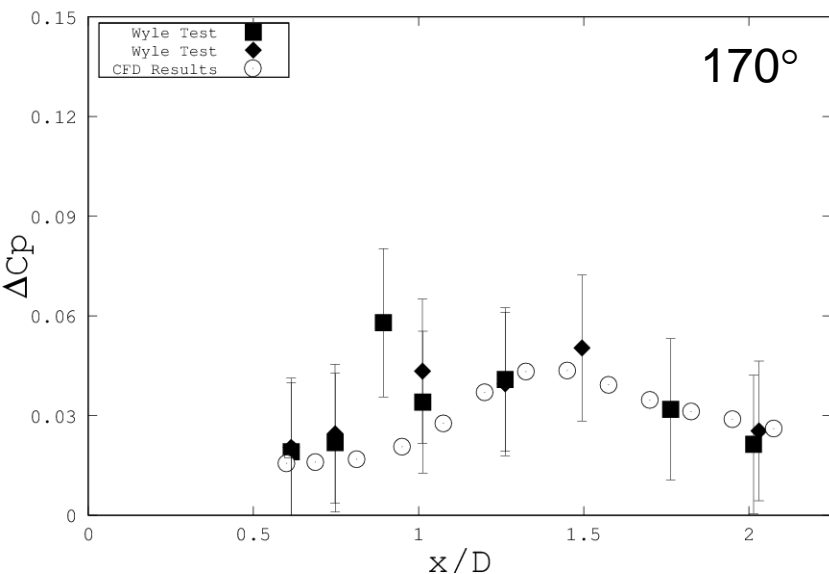
Comparisons with Experiments: C_p for $h/D = 2.0$



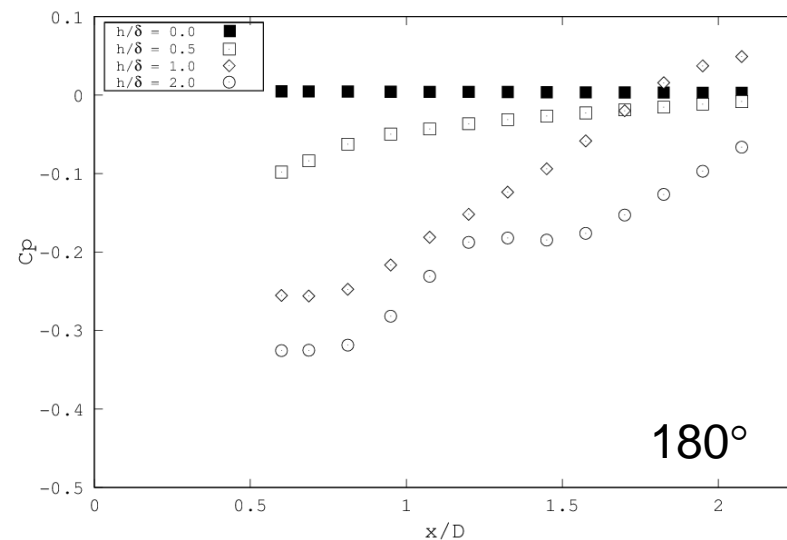
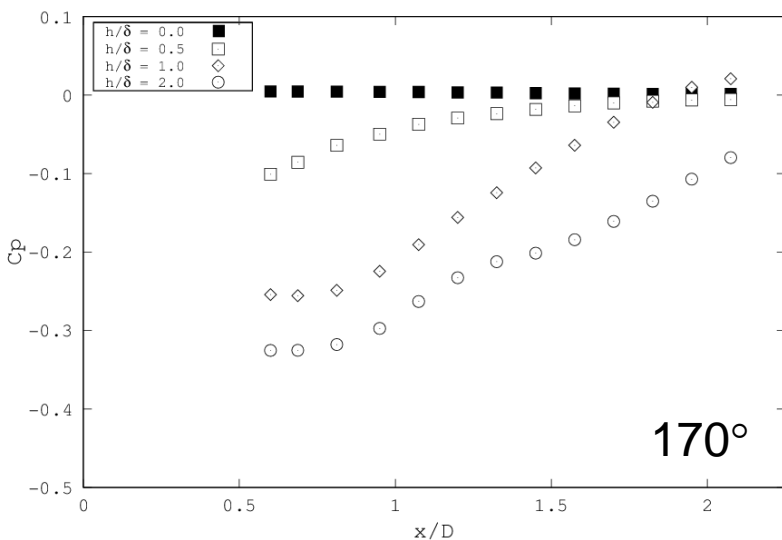
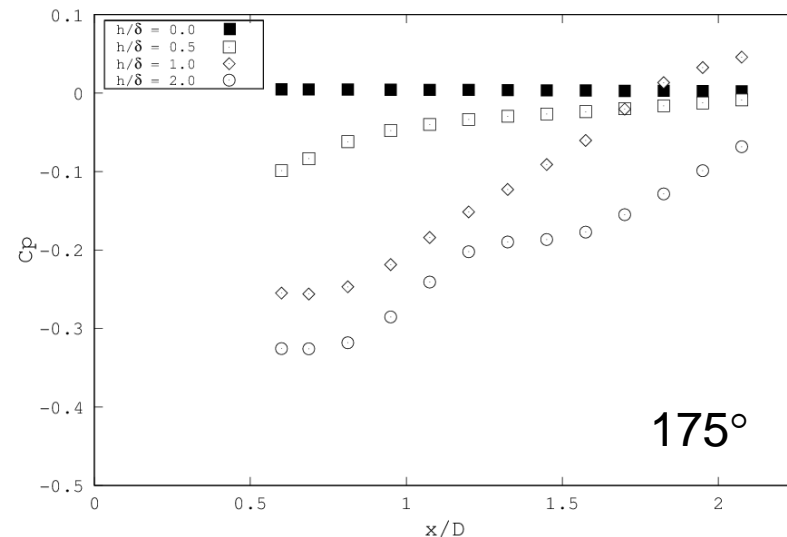
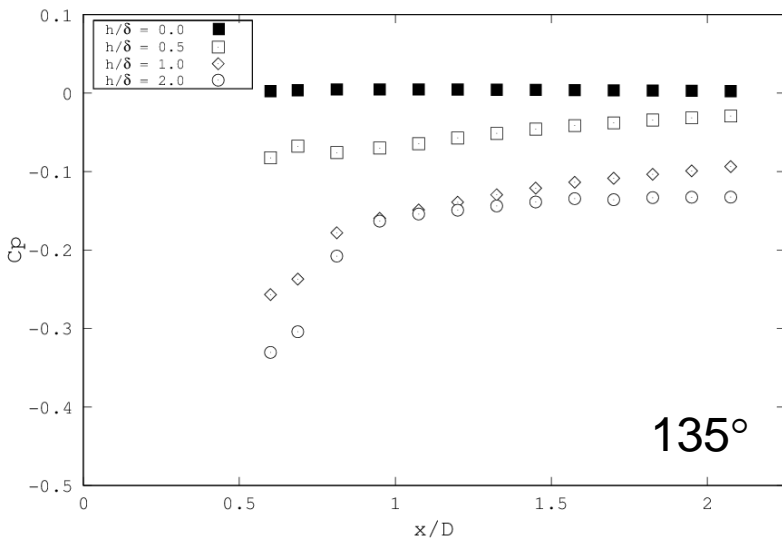
Comparisons with experiments: ΔC_p for $h/D = 2.0$



Comparisons with experiments: ΔC_p for $h/D = 2.0$



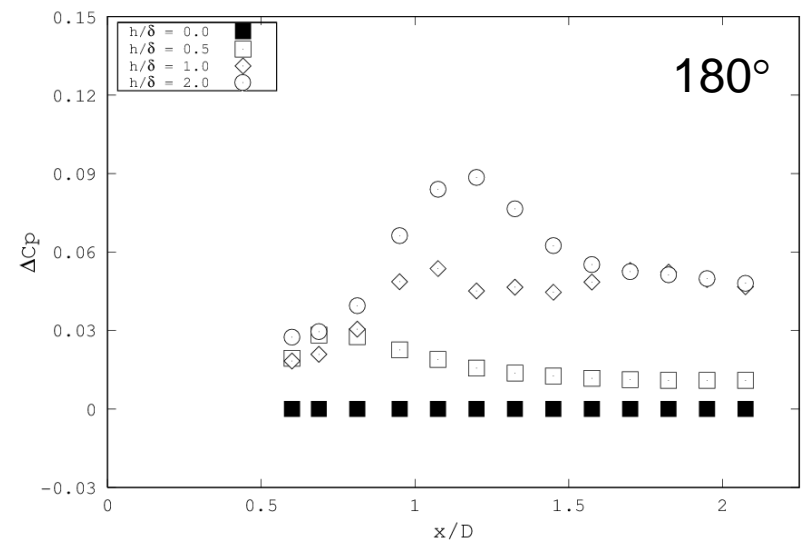
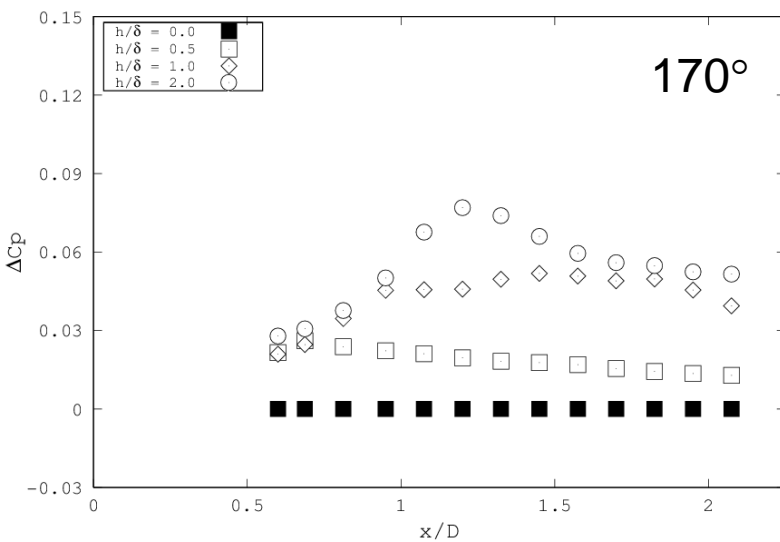
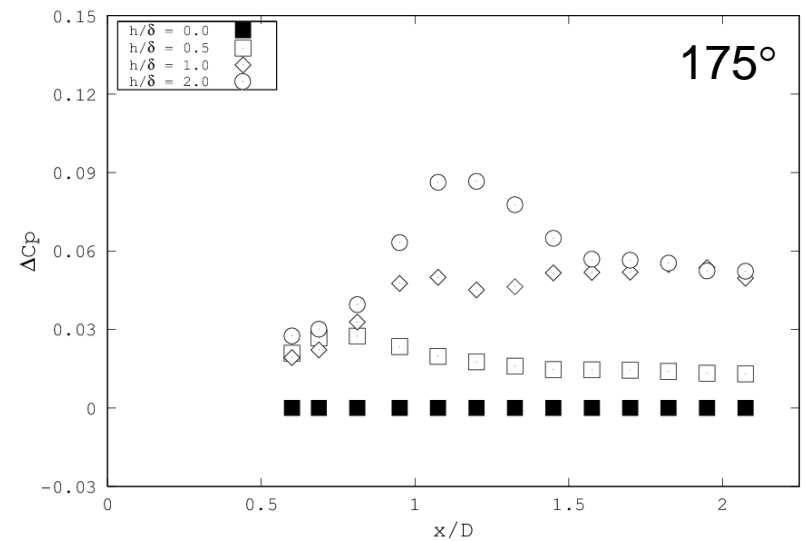
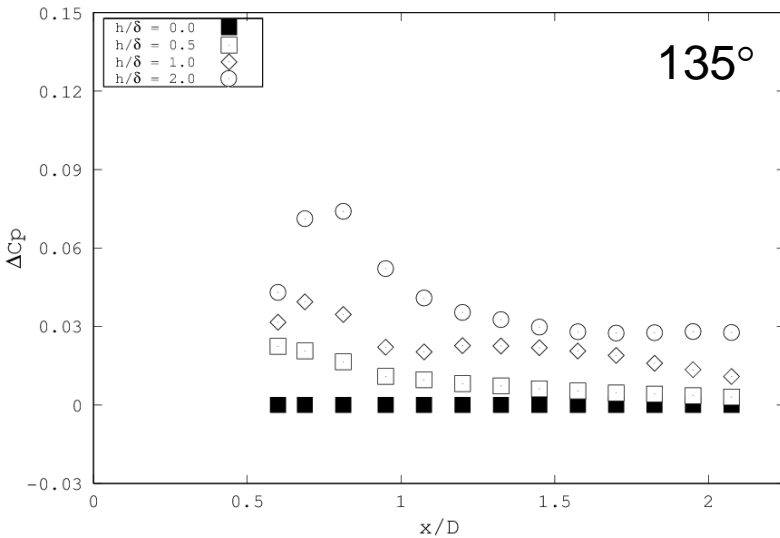
Effect of h/δ on C_p for a flat surface



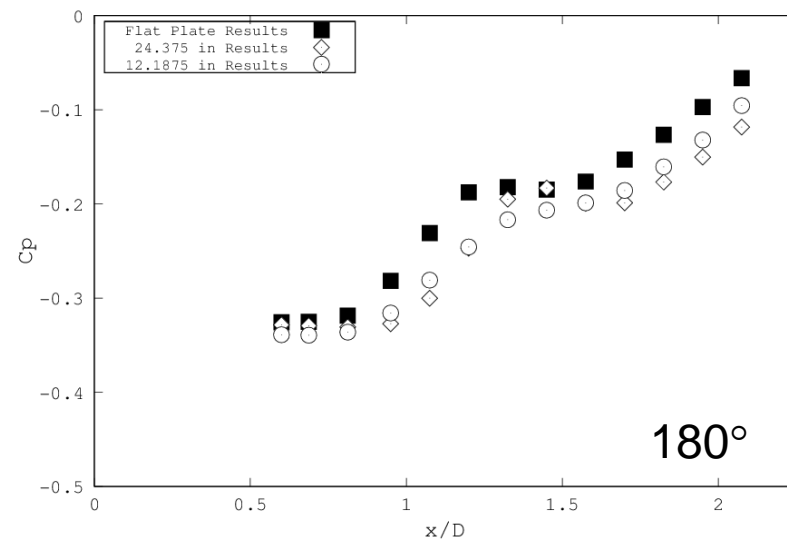
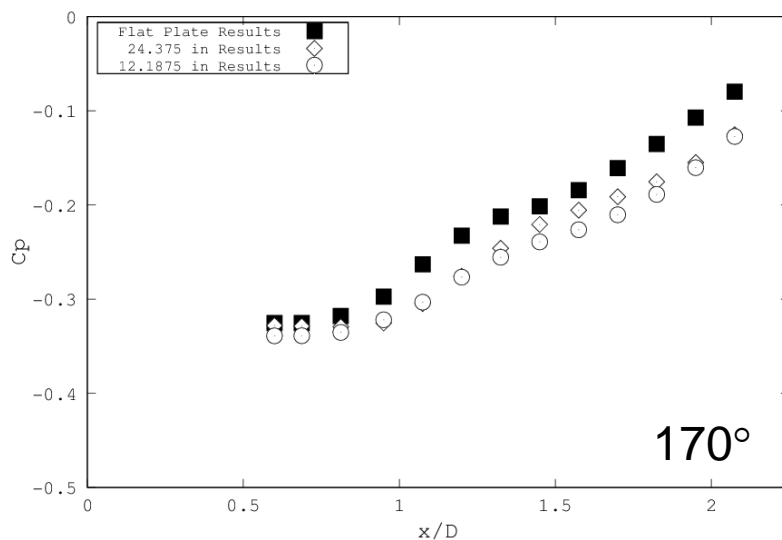
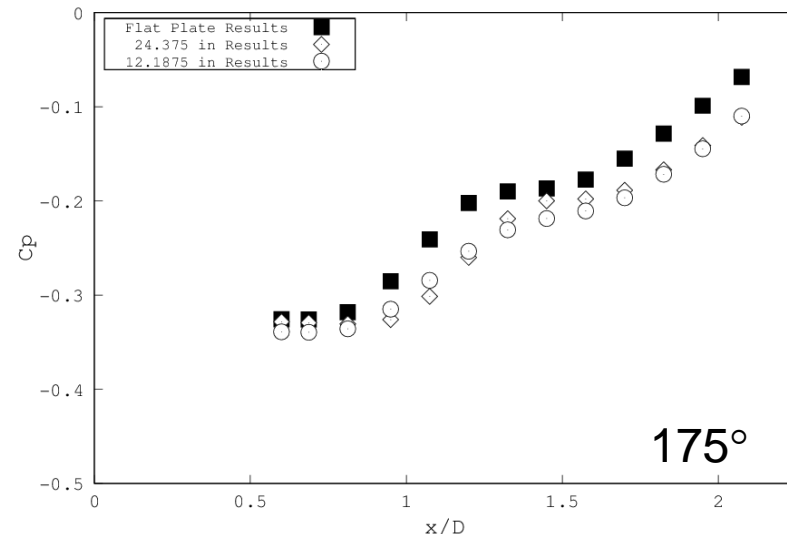
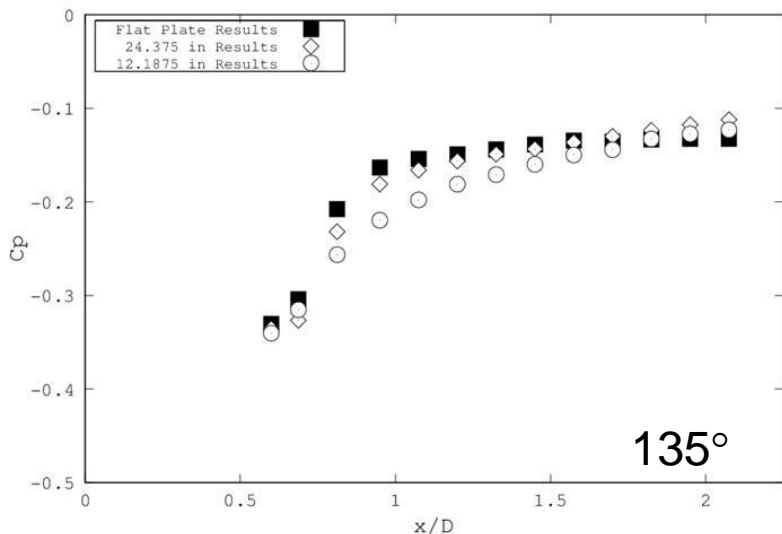
Tall protuberances have a similar trend; short protuberance approaches clean skin values.

Effect of h/δ on ΔC_p for a flat surface

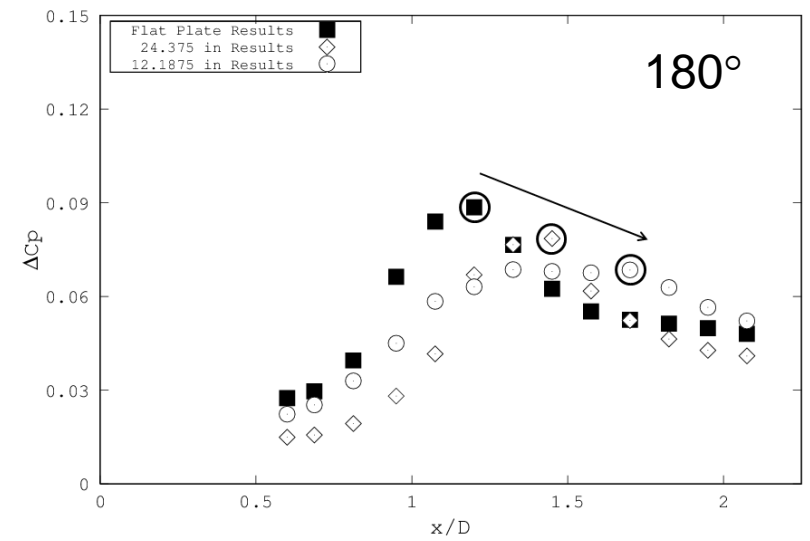
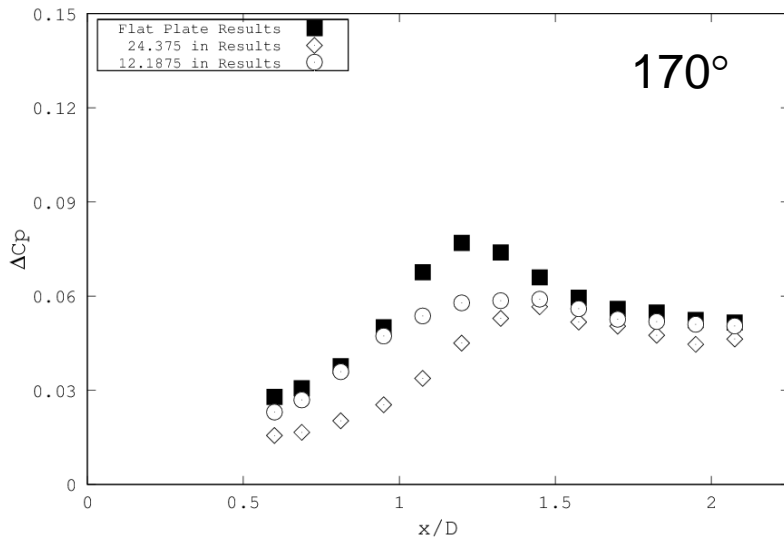
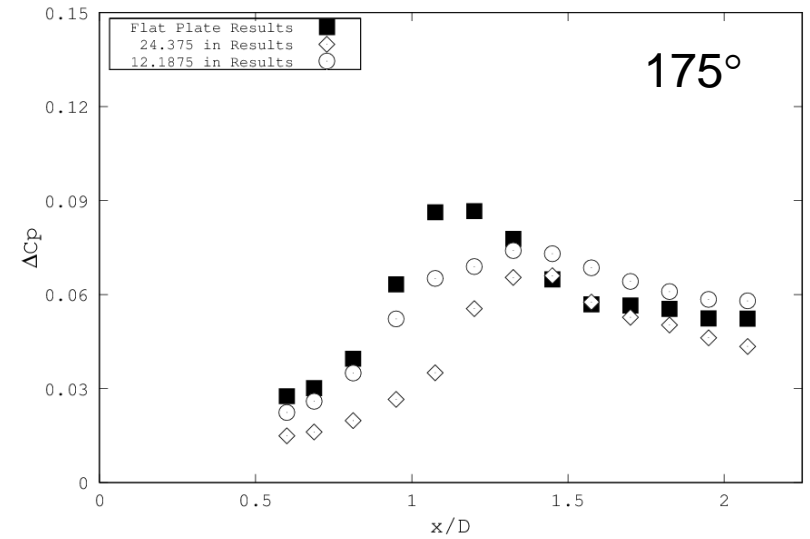
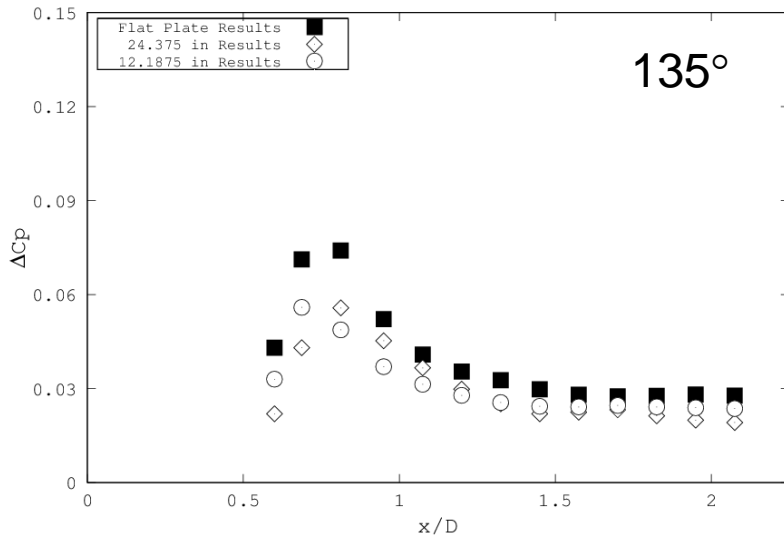
25



Effect of surface curvature on C_p for $h/\delta=2.0$

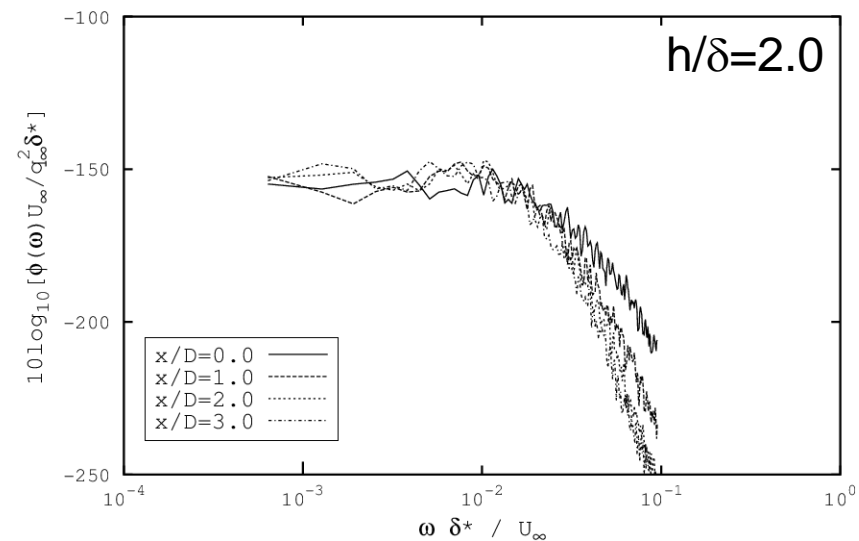
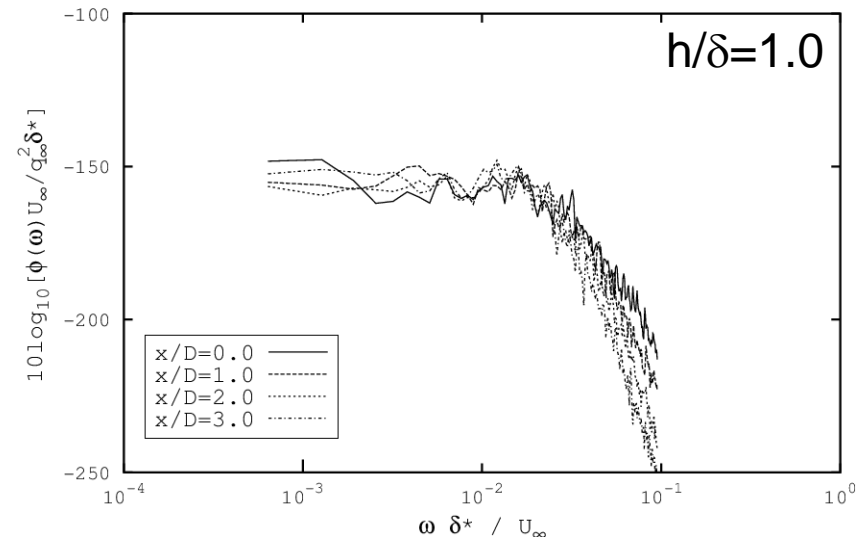
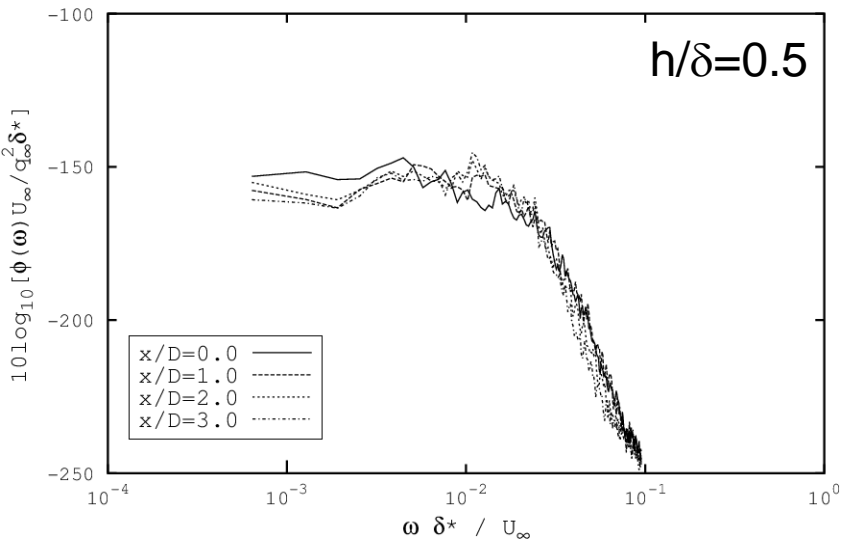


Effect of surface curvature on ΔC_p for $h/\delta = 2.0$



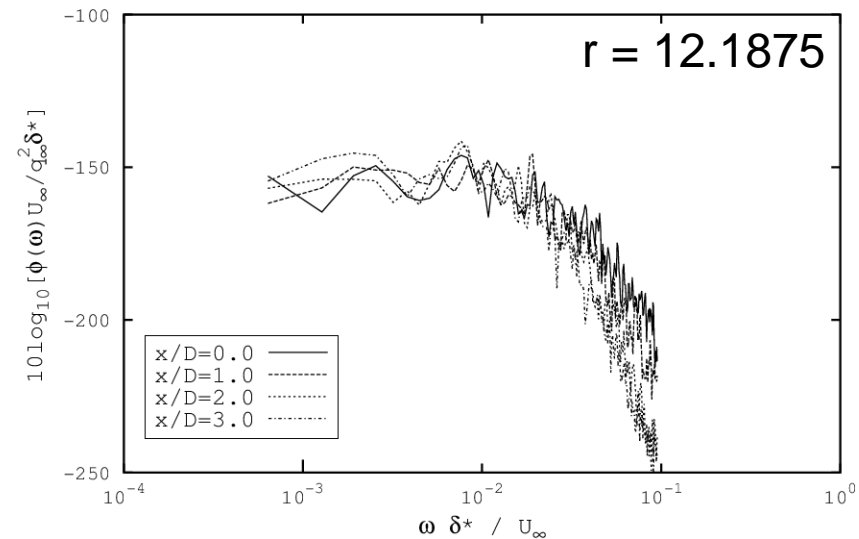
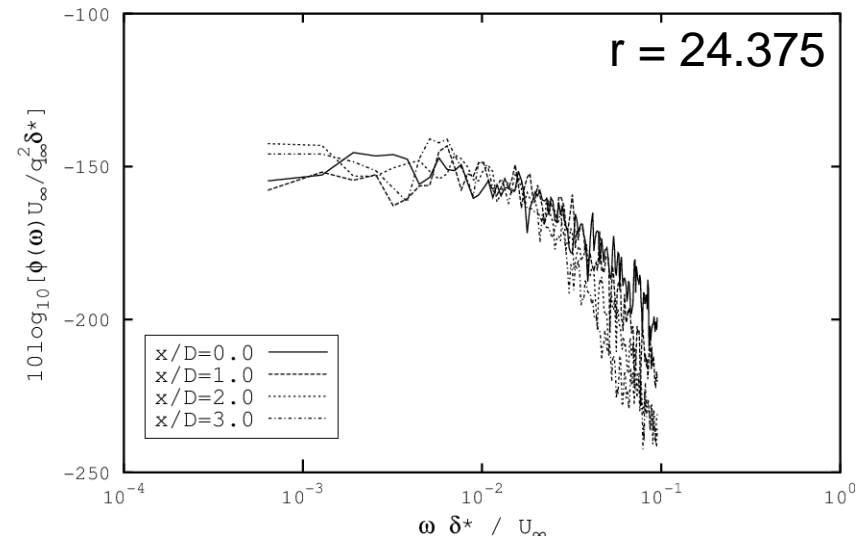
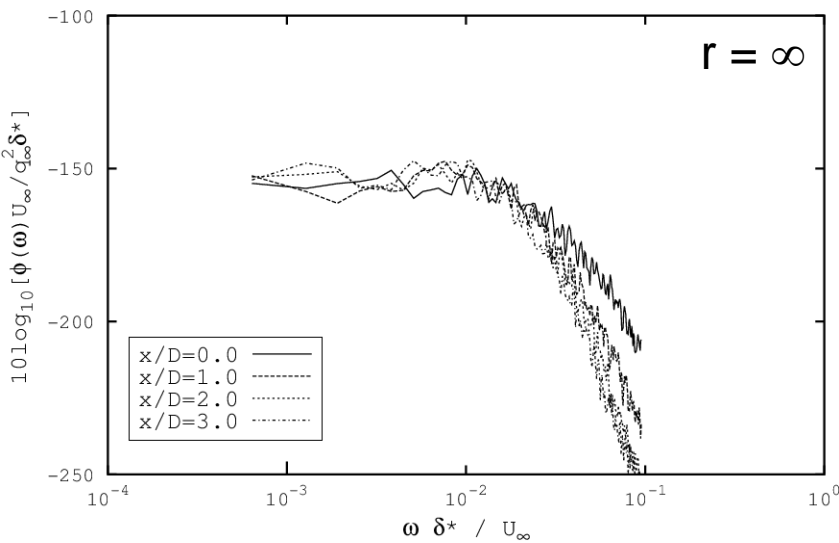
Wall Pressure Fluctuations

Frequency Spectra: Flat Surface



Outer scaling does well for low values of $\frac{\omega \delta^*}{U_{\infty}}$

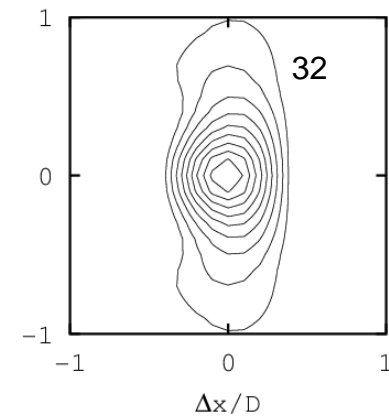
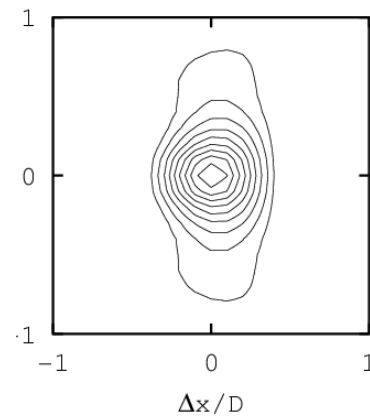
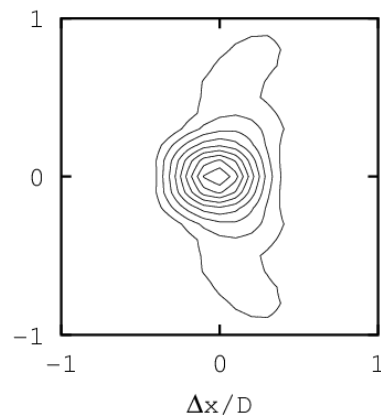
Frequency Spectra: $h/\delta=2.0$



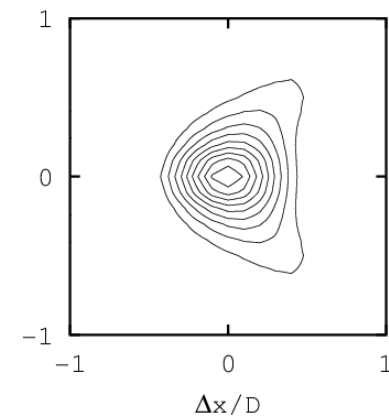
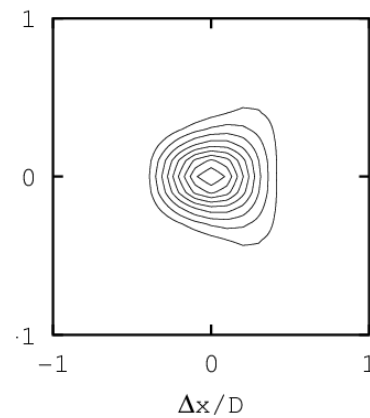
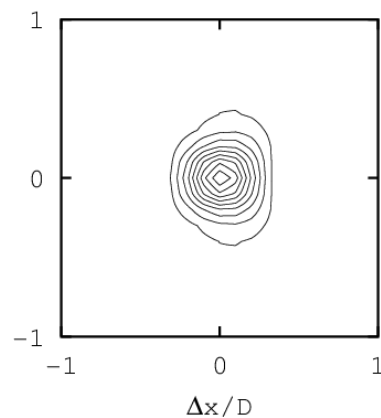
Outer scaling does well for low values of $\frac{\omega \delta^*}{U_\infty}$

Two Point Correlations of the Wall Pressure

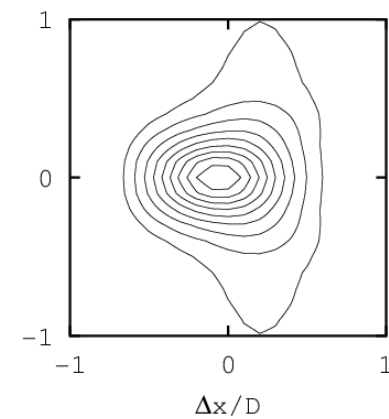
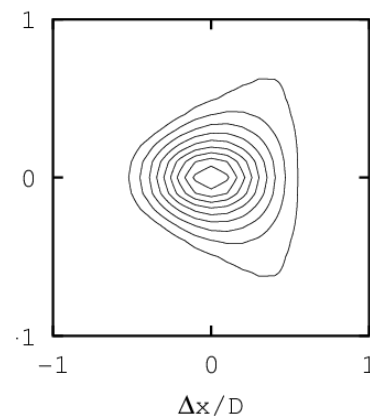
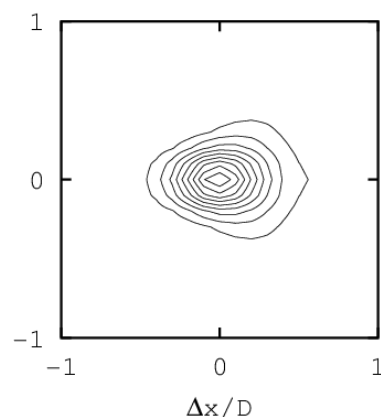
$h/\delta=0.5$



$h/\delta=1.0$



$h/\delta=2.0$



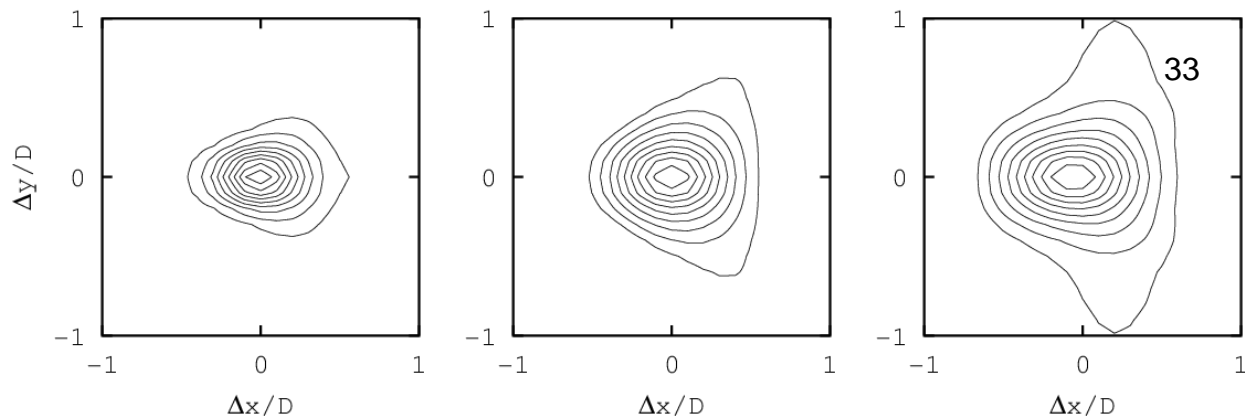
Flat Surface

$x/D=1.0$

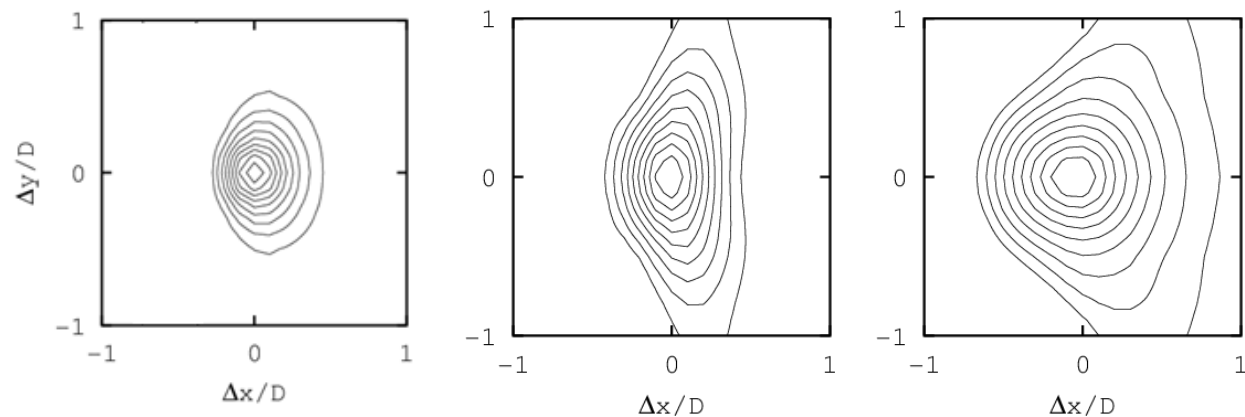
$x/D=2.0$

$x/D=3.0$

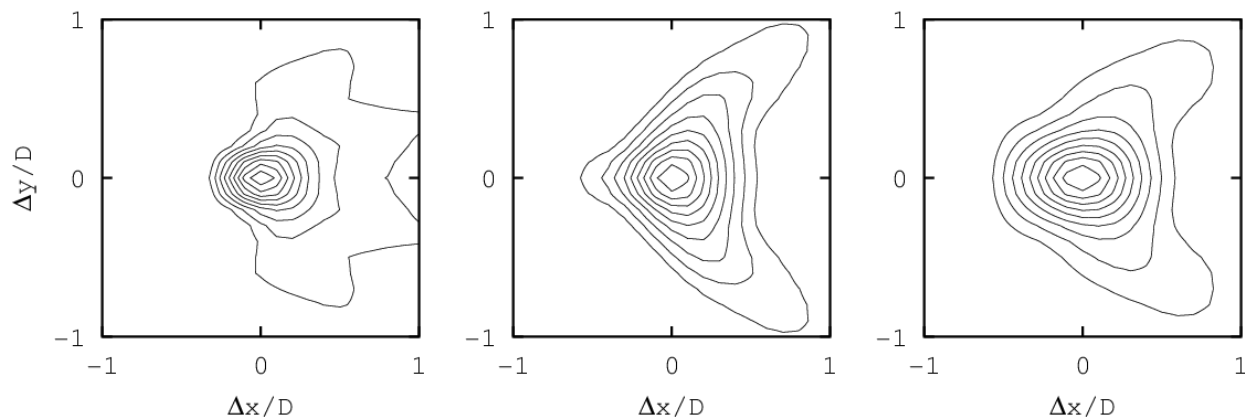
$$r = \infty$$



$$r = 24.375 \text{ in}$$



$$r = 12.1875 \text{ in}$$



Curved Surface:
 $h/\delta=2.0$

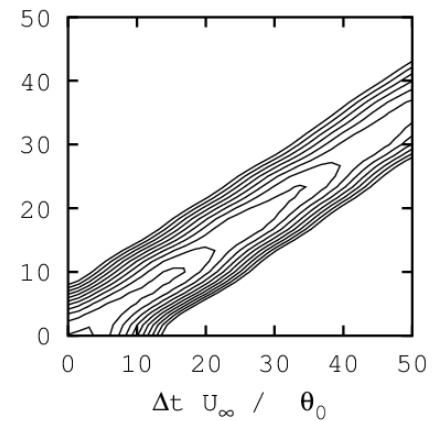
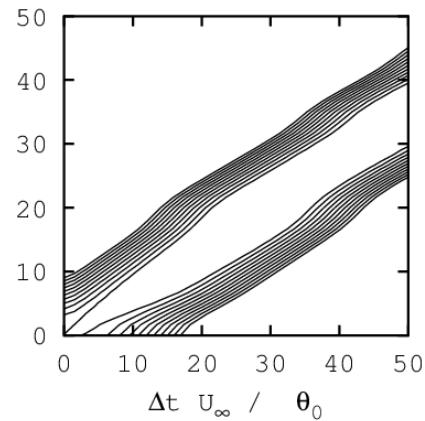
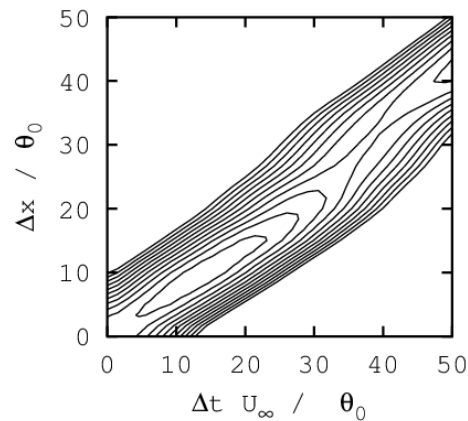
$x/D=1.0$

$x/D=2.0$

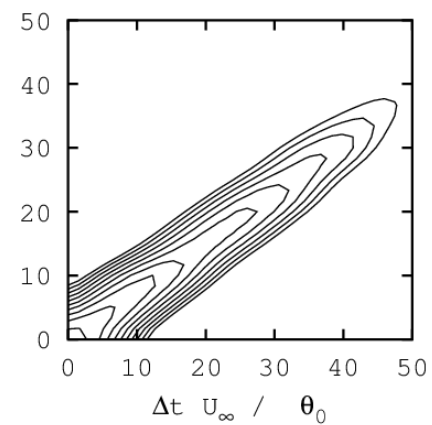
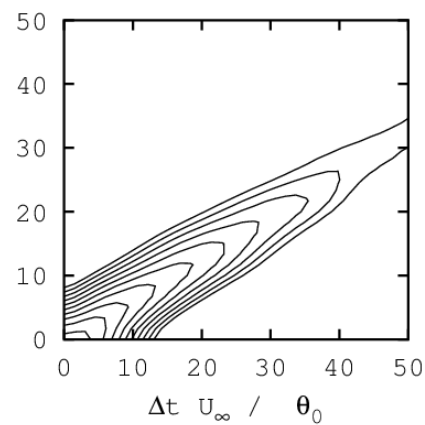
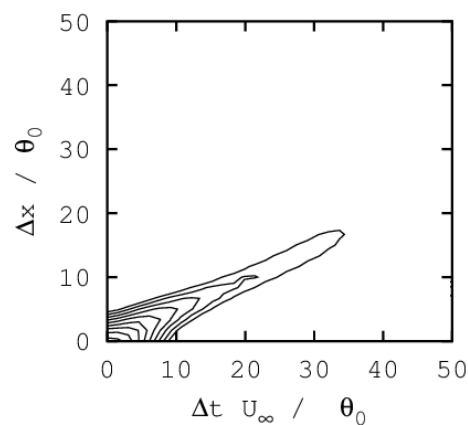
$x/D=3.0$

Space-Time Correlations of the Wall Pressure

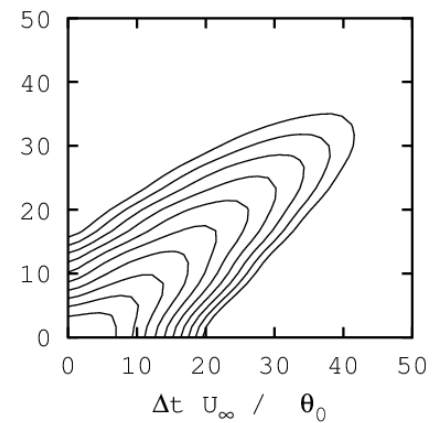
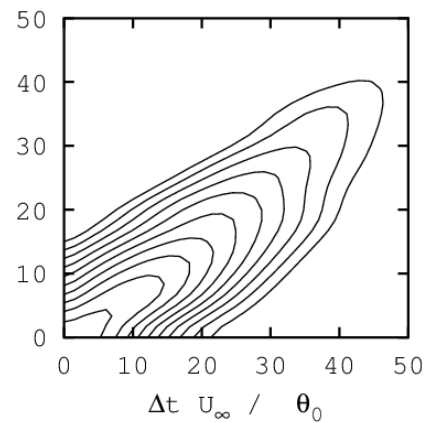
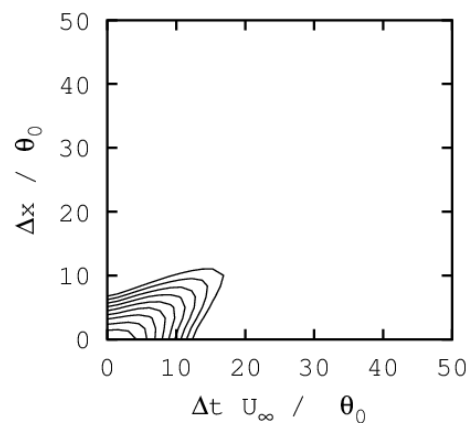
$h/\delta=0.5$



$h/\delta=1.0$



$h/\delta=2.0$



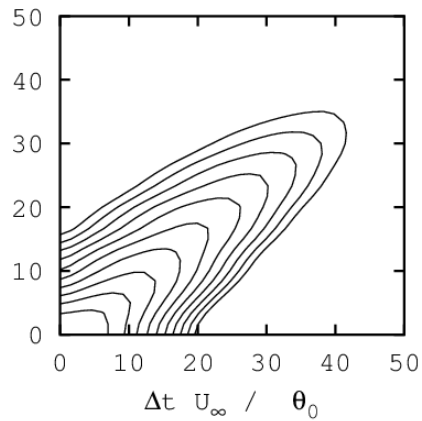
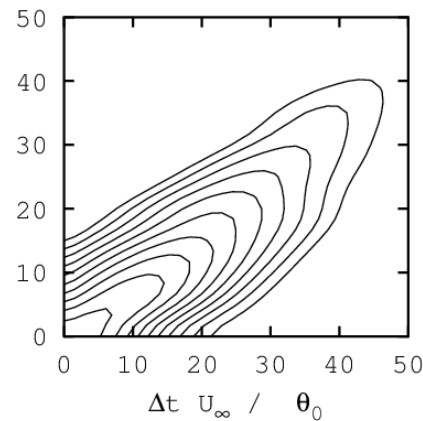
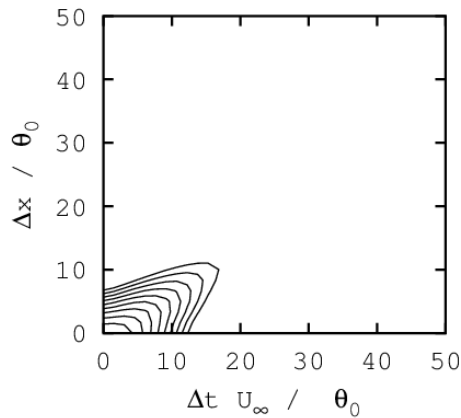
Flat Surface

$x/D=1.0$

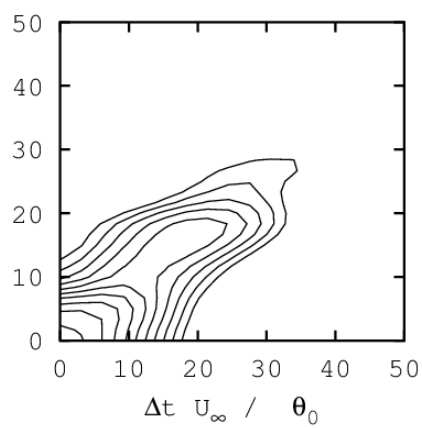
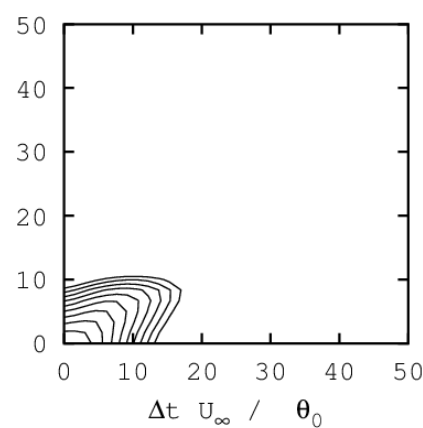
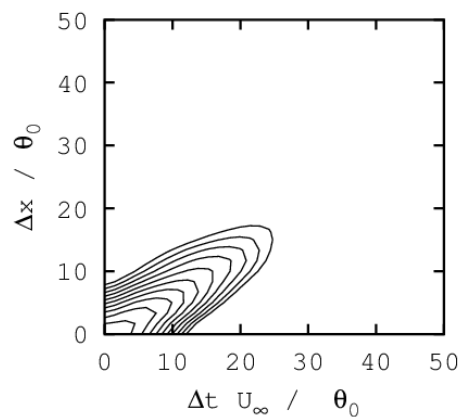
$x/D=2.0$

$x/D=3.0$

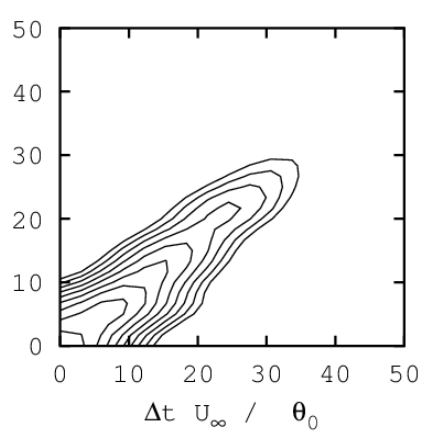
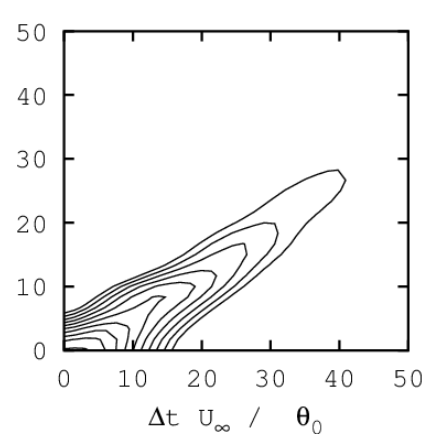
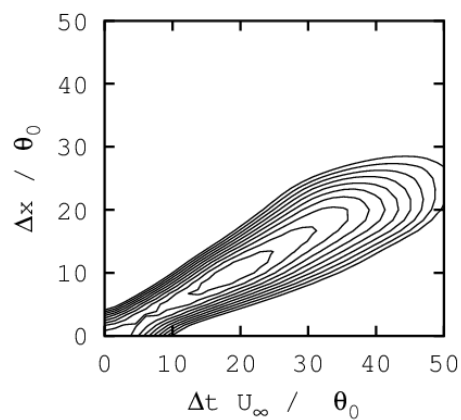
$r = \infty$



$r = 24.375$ in



$r = 12.1875$ in



$x/D = 1.0$

$x/D = 2.0$

$x/D = 3.0$

Curved Surface:

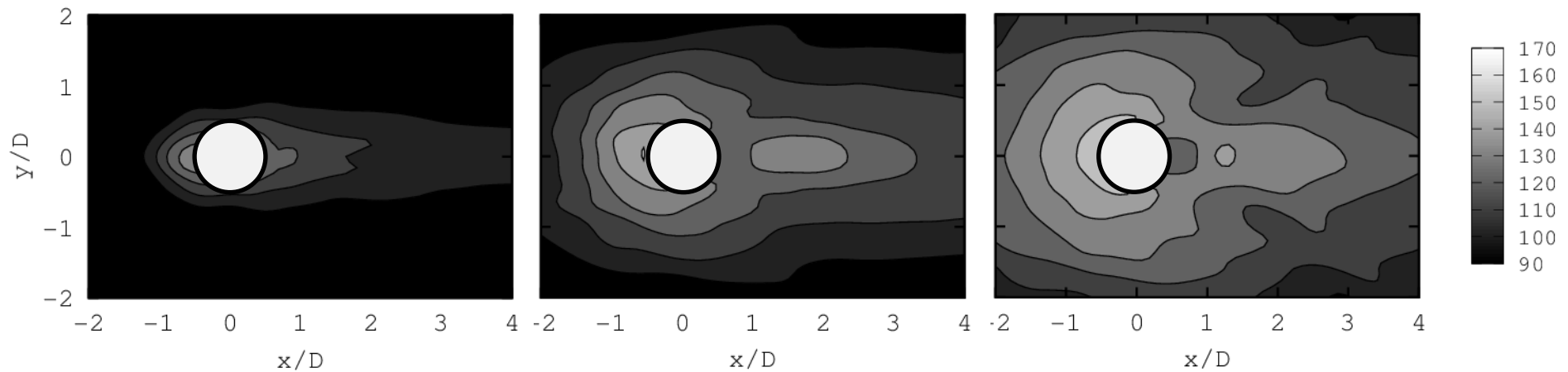
$$\frac{h}{\delta} = 2.0$$

OASPL: Flat Surface

$h/\delta=0.5$

$h/\delta=1.0$

$h/\delta=2.0$

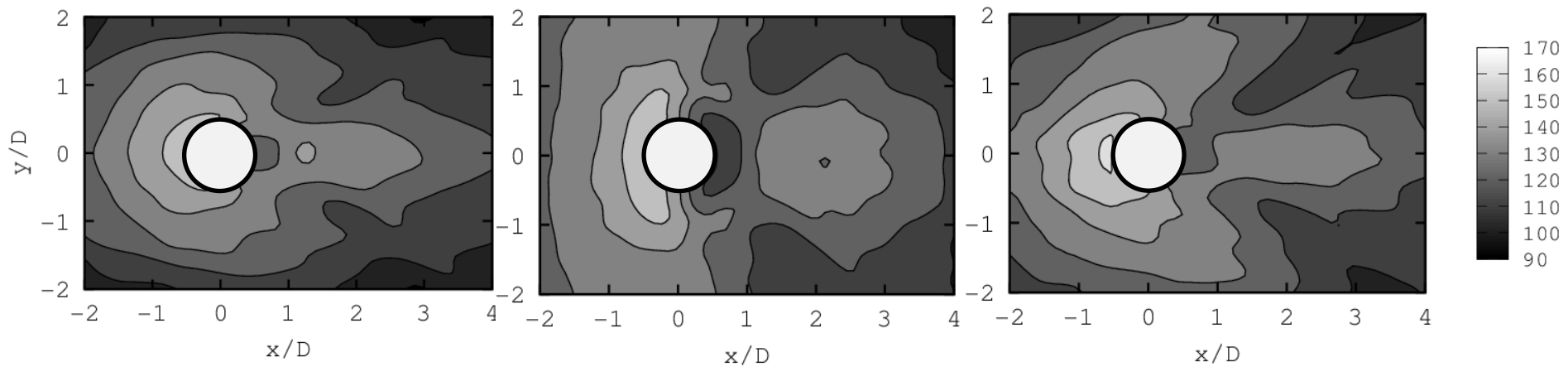


OASPL: Curved Surface $h/\delta=2.0$

Flat Plate

$r = 24.375$ in

$r = 12.1875$ in



Conclusions

- Results from the highly resolved DES computations are in good agreement with available experimental data for pressure coefficients.
- The effects of protuberance height and surface curvature on the wall pressure fluctuations and SWBLI have been assessed.
- Increasing protuberance height increases the OASPL on the surface.

Questions? Comments?

